U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-299 182

Energy from the West: Energy Resource Development Systems Report Volume VI: Geothermal

Oklahoma Univ, Norman Science and Public Policy Program

Prepared for

Environmental Protection Agency, Washington, DC Office of Energy, Minerals and Industry

Mar 79

United States
Environmental Protection
Agency

Office of Energy, Minerals, and
Industry
Washington DC 20460

Research and Development

PB 299182

EPA

Energy from the West

Energy Resource Development Systems Report Volume VI: Geothermal

Interagency Energy/Environment R&D Program Report

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-79-060f

2.

3. RECIPIENT'S ACCESSION NO. PB299182

4. TITLE AND SUBTITLE
ENERGY FROM THE WEST: ENERGY RESOURCE DEVELOPMENT SYSTEMS REPORT - VOLUME VI: GEOTHERMAL

5. REPORT DATE March 1979 issuing date

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) I.L. White; M.A. Chartock; R.L. Leonard; S.C. Ballard; M. Gilliland; R.A. Hall; E.J. Malecki; E.B. Rappaport; R.W. Rycroft; R.K. Freed; G.D. Miller

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Science & Public Policy Program
University of Oklahoma
601 Elm, Room 432
Norman, OK 73019

The Radian Corp.
P.O. Box 9948
Austin, TX 78766

10. PROGRAM ELEMENT NO. INE827

11. CONTRACT/GRANT NO. 68-01-1916

12. SPONSORING AGENCY NAME AND ADDRESS

U.S. Environmental Protection Agency
Office of Research & Development
Office of Energy, Minerals & Industry
Washington, D.C. 20460

13. TYPE OF REPORT AND PERIOD COVERED FINAL 1975 - 1978

14. SPONSORING AGENCY CODE EPA/600/17

15. SUPPLEMENTARY NOTES
This project is part of the EPA-planned and coordinated Federal Interagency Energy/Environment R&D Program.

16. ABSTRACT

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This report describes the technologies likely to be used for development of coal, oil shale, uranium, oil, natural gas, and geothermal resources in eight western states (Arizona, Colorado, Montana, New Mexico, North Dakota, South Dakota, Utah, and Wyoming). It is part of a three-year "Technology Assessment of Western Energy Resource Development." The study examines the development of these energy resources in the eight states from the present to the year 2000. Other reports describe the analytic structure and conduct of the study, the impacts likely to result when these resources are developed, and analyze policy problems and issues likely to result from that development. The report is published in six volumes. Volume 1 describes the study, the technological activities such as exploration, extraction, and conversion for developing the resource, and laws and regulations which affect the development of more than one of the six resources considered in the study. The remaining five volumes are resource specific: Volume 2, Coal; Volume 3, Oil Shale; Volume 4, Uranium; Volume 5, Oil and Natural Gas; and Volume 6, Geothermal. Each of these volumes provides information on input materials and labor requirements, outputs, residuals, energy requirements, economic costs, and resource specific state and federal laws and regulations.

IT

17. KEY WORDS AND DOCUMENT ANALYSIS (Circle One or More)

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Energy Conversion	Fuel Cycle: Geothermal Extraction, Processing and Conversion	6F 8A 8F 8H 10A 10B 7B 7C 13B

18. DISTRIBUTION STATEMENT Unlimited	**19. SECURITY CLASS** *(This Report)* Unclassified	**21. NO. OF PAGES** ~~219~~ 221
	20. SECURITY CLASS *(This page)* Unclassified	**22. PRICE** PC A10 / MF A01

EPA-600/7-79-060f
March 1979

Energy From the West: Energy Resource Development Systems Report

Volume VI: Geothermal

By
Science and Public Policy Program
University of Oklahoma

Irvin L. White
Michael A. Chartock
R. Leon Leonard
Steven C. Ballard
Martha Gilliland
Timothy A. Hall
Edward J. Malecki
Edward B. Rappaport
Robert W. Rycroft
Rodney K. Freed
Gary D. Miller

Managers,
Energy Resource Development Systems
R. Leon Leonard, Science and Public Policy
University of Oklahoma
Clinton E. Burklin

C. Patrick Bartosh
Clinton E. Burklin
William R. Hearn
Gary D. Jones
William J. Moltz
Patrick J. Murin

Prepared for:
Office of Research and Development
U. S. Environmental Protection Agency
Washington, D.C. 10460

Project Officer:
Steven E. Plotkin
Office of Energy, Minerals and Industry

Contract Number 68-01-1916

Energy
from
the
West

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FORWARD

The production of electricity and fossil fuels inevitably impacts Man and his environment. The nature of these impacts must be thoroughly understood if balanced judgements concerning future energy development in the United States are to be made. The Office of Energy, Minerals and Industry (OEMI), in its role as coordinator of the Federal Energy/Environment Research and Development Program, is responsible for producing the information on health and ecological effects - and methods for mitigating the adverse effects - that is critical to developing the Nation's environmental and energy policy. OEMI's Integrated Assessment Program combines the results of research projects within the Energy/Environment Program with research on the socioeconomic and political/institutional aspects of energy development, and conducts policy - oriented studies to identify the tradeoffs among alternative energy technologies, development patterns, and impact mitigation measures.

The Integrated Assessment Program has supported several "technology assessments" in fulfilling its mission. Assessments have been supported which explore the impact of future energy development on both a nationwide and a regional scale. Current assessments include national assessments of future development of the electric utility industry and of advanced coal technologies (such as fluidized bed combustion). Also, the Program is conducting assessments concerned with multiple-resource development in two "energy resource areas":

- Western coal states
- Lower Ohio River Basin

This report, which describes the technologies likely to be used for developing six energy resources in eight western states, is one of three major reports produced by the "Technology Assessment of Western Energy Resource Development" study. (The other two reports are an impact analysis report and a policy analysis report.) The report is divided into six volumes. The first volume describes the study, the organization of this report and briefly outlines laws and regulations which affect the development of more than one of the six resources considered in the study. The remaining five volumes are resource specific and describe the resource base, the technological activities such as exploration, extraction and conversion for developing the resource, and resource specific laws and regulations. This report is both a compendium of information and a planning handbook. The descriptions of the various energy development technologies and the extensive compilations of technical baseline information are written to be easily understood by laypersons. Both professional planners and interested citizens should find it quite easy to use the information presented in this report to make general but useful comparisons of energy technologies and energy development alternatives, especially when this report is used in conjunction with the impact and policy analysis reports mentioned above.

Your review and comments on these reports are welcome. Such comments will help us to improve the usefulness of the products produced by our Integrated Assessment Program.

Steven R. Reznek

Acting Deputy Assistant Administrator
for Energy, Minerals and Industry

PREFACE

This Energy Resource Development System (ERDS) report has been prepared as part of "A Technology Assessment of Western Energy Resource Development" being conducted by an interdisciplinary research team from the Science and Public Policy Program (S&PP) of the University of Oklahoma for the Office of Energy, Minerals and Industry (OEMI), Office of Research and Development, U.S. Environmental Protection Agency (EPA). This study is one of several conducted under the Integrated Assessment Program established by OEMI in 1975. Recommended by an interagency task force, the purpose of the Program is to identify economically, environmentally, and socially acceptable energy development alternatives. The overall purposes of this particular study were to identify and analyze a broad range of consequences of energy resource development in the western U.S. and to evaluate and compare alternative courses of action for dealing with the problems and issues either raised or likely to be raised by development of these resources.

The Project Director was Irvin L. (Jack) White, Assistant Director of S&PP and Professor of Political Science at the University of Oklahoma. White is now Special Assistant to Dr. Stephen J. Gage, EPA's Assistant Administrator for Research and Development. R. Leon Leonard, now a senior scientist with Radian Corporation in Austin, Texas, was a Co-Director of the research team, Associate Professor of Aeronautical, Mechanical, and Nuclear Engineering and a Research Fellow in S&PP at the University of Oklahoma. Leonard was responsible for editing and managing the production of this report. EPA Project Officer was Steven E. Plotkin, Office of Energy, Minerals and Industry, Office of Research and Development. Plotkin is now with the Office of Technology Assessment. Other S&PP team members are: Michael A. Chartock, Assistant Professor of Zoology and Research Fellow in S&PP and the other Co-Director of the team; Steven C. Ballard, Assistant Professor of Political Science and Research Fellow in S&PP; Edward J. Malecki, Assistant Professor of Geography and Research Fellow in S&PP; Edward B. Rappaport, Visiting Assistant Professor of Economics and Research Fellow in S&PP; Frank J. Calzonetti, Research Associate (Geography) in S&PP; Timothy A. Hall, Research Associate (Political Science); Gary D. Miller, Graduate Research Assistant (Civil Engineering and Environmental Sciences); and Mark S. Eckert, Graduate Research Assistant (Geography).

Chapters 3-7 were prepared by the Radian Corporation, Austin, Texas, under subcontract to the University of Oklahoma. In each of these chapters, Radian is primarily responsible for the description of the resource base and the technologies and S&PP is primarily responsible for the description of laws and regulations. The Program Manager at Radian was C. Patrick Bartosh. Clinton E. Burklin was responsible for preparation of these five chapters. Other contributors at Radian were: William R. Hearn, Gary D. Jones, William J. Moltz, and Patrick J. Murin.

Additional assistance in the preparation of the ERDS report was provided by Martha W. Gilliland, Executive Director, Energy Policies Studies, Inc., El Paso, Texas; Rodney K. Freed, Attorney, Shawnee, Oklahoma; and Robert W. Rycroft, Assistant Professor of Political Science, University of Denver, Denver, Colorado.

ABSTRACT

This report describes the technologies likely to be used for development of coal, oil shale, uranium, oil, natural gas, and geothermal resources in eight western states (Arizona, Colorado, Montana, New Mexico, North Dakota, South Dakota, Utah, and Wyoming). It is part of a three-year "Technology Assessment of Western Energy Resource Development." The study examines the development of these energy resources in the eight states from the present to the year 2000. Other reports describe the analytic structure and conduct of the study, the impacts likely to result when these resources are developed, and analyze policy problems and issues likely to result from that development. The report is published in six volumes. Volume 1 describes the study, the technological activities such as exploration, extraction, and conversion for developing the resource, and laws and regulations which affect the development of more than one of the six resources considered in the study. The remaining five volumes are resource specific: Volume 2, Coal; Volume 3, Oil Shale; Volume 4, Uranium; Volume 5, Oil and Natural Gas; and Volume 6, Geothermal. Each of these volumes provides information on input materials and labor requirements, outputs, residuals, energy requirements, economic costs, and resource specific state and federal laws and regulations.

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CONVERSION FACTORS

English Units/Metric Units

To Convert From	To	Multiply By
acre	m^2	4046.9
acre-ft/year	gpm	0.6200
acre-ft/year	m^3/yr	1233.5
barrel	gal	42
barrel	m^3	0.15899
Btu	joule	1054.4
Btu/hour	watt	0.2931
Btu/pound	joule/gram	2.32
foot	m	0.3048
gallon	m^3	0.003785
lb	kg	0.4536
psi	pascal	6894.8
quad	Btu	10^{15}
quad	joule	$\sim 10^{18}$
ton	kg	907.18

ACKNOWLEDGEMENTS

Patrick J. Murin of the Radian Corporation and Gary D. Miller of the Science and Public Policy Program at the University of Oklahoma had primary responsibility for preparation of this volume of the Energy Resource Development Systems (ERDS) Report. The social controls sections were prepared by Rodney K. Freed and R. Leon Leonard of the Science and Public Policy Program. Mr. Freed is now an attorney in Shawnee, Oklahoma and Dr. Leonard is now a senior scientist with the Radian Corporation in Austin, Texas.

The research reported here could not have been completed without the assistance of a dedicated administrative support staff. At Radian Corporation, Mary Harris was responsible for typing of this volume, and at the University of Oklahoma, Janice Whinery, Assistant to the Director, coordinated assembly of the volumes of the ERDS Report.

Nancy Ballard, graphics arts consultant, designed the title page.

Steven E. Plotkin, EPA Project Officer, has provided continuing support and assistance in the preparation of this report.

The individuals listed below participated in the review of this volume of the ERDS Report and provided information for its preparation. Although these critiques were extremely helpful, none of these individuals is responsible for the content of this volume. This volume is the sole responsibility of the Science and Public Policy interdisciplinary research team and the Radian Corporation.

Mr. George Boulter
Office of Energy Activities
Environmental Protection Agency
Region VIII
Denver, Colorado

Mr. Robert P. Hartley
Program Manager for Geothermal Energy
Industrial Environmental Research Laboratory
Environmental Protection Agency
Cincinnati, Ohio

Dr. John Hoover
Energy and Environmental
Systems
Argonne National Laboratory
Chicago, Illinois

Dr. Frank Maslan
Office of Technology Assessment
U.S. Congress
Washington, D.C.

Mr. Robert Oliver
Program Manager, Planning
Branch
Division of Geothermal Energy
Department of Energy
Washington, D.C.

Dr. D.R. Rao
New Mexico Energy Institute
New Mexico State University
Las Cruces, New Mexico

Mr. Douglas M. Sacarto
Associate Director
Geothermal Policy Project
National Conference of
State Legislatures
Denver, Colorado

Dr. Morton C. Smith
Geosciences Division
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

Dr. Kenneth Starling
School of Chemical Engineering
and Materials Sciences
University of Oklahoma
Norman, Oklahoma

Mr. Randy Stevens
Division of Geothermal Energy
Department of Energy
Washington, D.C.

CHAPTER 8

THE GEOTHERMAL RESOURCE DEVELOPMENT SYSTEM

8.1 INTRODUCTION

This document is one of several reports issued in support of a "Technology Assessment of Western Energy Resource Development," a project jointly conducted by the Science and Public Policy Program of the University of Oklahoma and the Radian Corporation of Austin, Texas. The project is funded by the Office of Energy, Minerals, and Industry, Office of Research and Development, Environmental Protection Agency under Contract 68-01-1916. The "Technology Assessment of Western Energy Resource Development" describes the development of energy resources in eight western states. These states are: Arizona, Colorado, Montana, New Mexico, North Dakota, South Dakota, Utah, and Wyoming.

This document is issued as Chapter 8 of the "Energy Resources Development System" (ERDS) report. For each of six energy resources, the ERDS report describes the energy resource base, the technologies used to develop and utilize the resource, the inputs and outputs for each development technology, and the laws and regulations applying to the deployment and operation of each technology. Resources described in the ERDS report are: coal, oil shale, uranium, oil, natural gas, and geothermal energy. This chapter discusses the development of the geothermal energy resource.

In the broadest terms, geothermal energy can be defined as heat emanating from the earth. This heat is derived from the decay of radioactive elements (chiefly uranium and thorium), friction (tidal and crustal plate motion), and possibly primeval heat. Localized areas of concentrated heat may form as the heat flows radially outward. In certain regions of the earth's crust, these areas of concentrated heat may be used for electricity generation or as a source of low grade heat.

Man has known about goethermal energy since ancient times. The Romans used hot geysers for baths and for space heating. The Italians were extracting boric acid from steam jets near Larderello, Italy, in the 19th century. Use of the Larderello steam jets for electricity generation began in 1904.

The United States first used geothermal energy for electricity generation in 1960 at The Geysers area in California. To date, The Geysers area remains the only site of commercial electricity production from geothermal energy in the U.S. Pacific Gas and Electric Company currently is generating about 500 megawatts from The Geysers dry steam field. By 1985, production at The Geysers is expected to amount to 1800-2130 MW_e Additional electricity production from other geothermal resources is expected to amount to 1220-1960 MW_e by 1985.[1,2] With these and other additions, geothermal energy may provide about one percent (under very favorable conditions, several percent) of

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[1] Resources Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency. Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, pp. 15, 16, 19, 25.

[2] LaMori, Phillip N. "Growth in Utilization of Hydrothermal Geothermal Resources." Geothermal Resources Council, Transactions. Vol. 1. May 1977. pp. 181-182.

the electricity production in the U.S. by the year 2000. Although its national role is small, geothermal energy can be a significant producer of electricity in certain local areas (*e.g.*, California).[1]

Geothermal resources may also be used for various direct thermal or other nonelectric purposes. For example, fresh water can be produced by condensing steam from liquid- or vapor-dominated geothermal resources. Some geothermal fluids contain significant quantities of extractable minerals. Direct space heating with geothermal water is currently employed in the U.S. at Klamath Falls, Oregon, and Boise, Idaho. Direct thermal and other nonelectrical uses are most important in the utilization of low-temperature geothermal fluids.

This chapter describes the technologies, inputs, outputs, rules, and regulations associated with the development of geothermal energy resources. The chapter comprises five major sections which begin with a general description of the geothermal energy resource. The remaining sections describe the steps or activities involved in developing geothermal energy.

Section 8.2 summarizes the input requirements and outputs identified in this study as resulting from the development and utilization of the western geothermal energy resource.

Section 8.3, Resource Characteristics, describes the geothermal energy resource in terms of geology, location, quantity, physical and chemical characteristics, and ownership.

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[1] Science and Public Policy Program, University of Oklahoma. Energy Alternatives: A Comparative Analysis. Prepared for CEQ ERDA, EPA, FEA, FPC, DOI, NSF, CEQ Contract No. EQ4AC034. Washington, D.C.: U.S. Government Printing Office. May 1975, p. 8-1.

The remaining sections (Sections 8.4 through 8.7) describe the development of geothermal energy as a basic sequence of "activities". In the development of geothermal energy resources, these activities include: exploration, extraction (both drilling and production phases), and electricity generation or nonelectric utilizations. These activities are illustrated in Figure 8-1. For each activity, "technological alternatives" are discussed which represent potential development options (*e.g.*, various drilling technologies).

When available, input requirements and outputs for each technological alternative or activity are presented. Input requirements discussed in this report include: manpower, materials and equipment, economics, water, land, and ancillary energy. The outputs describe the residuals from each activity or technological alternative that may pose environmental hazards. The outputs described in the report are air emissions, water effluents, solid wastes, noise pollution, occupational health and safety hazards, and odor. Social controls (*i.e.*, laws and regulations) governing the development of geothermal energy resources are also discussed.

Input requirements and outputs reported herein mostly describe vapor-dominated geothermal fluids used for electricity generation. Liquid-dominated fluids offer greater potential for both electrical and other uses. However, use of liquid-dominated resources is relatively undeveloped in the United States. Other geothermal resources (*e.g.*, hot dry rock resources) are also relatively undeveloped. When possible, inputs and outputs for these undeveloped resources are reported.

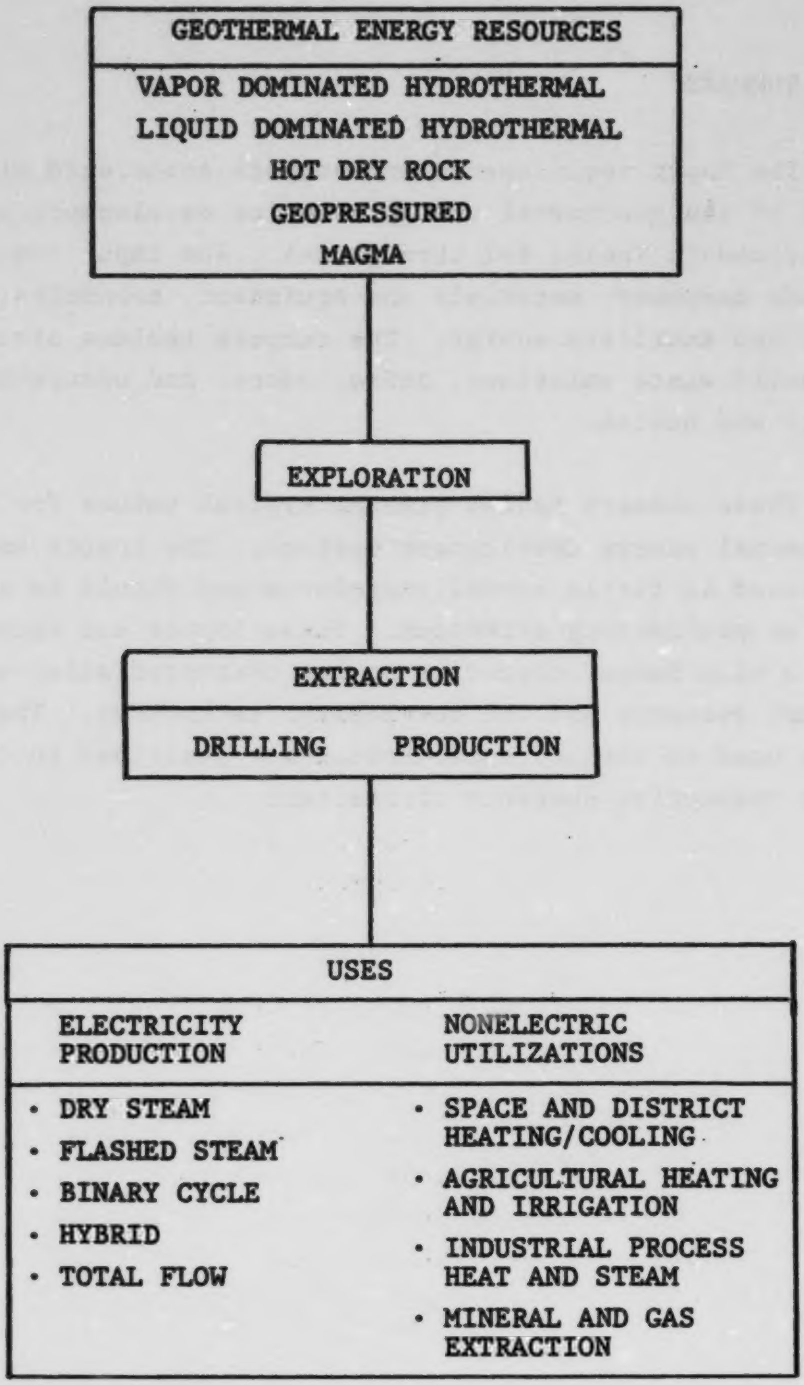
GEOTHERMAL ENERGY RESOURCES
VAPOR DOMINATED HYDROTHERMAL
LIQUID DOMINATED HYDROTHERMAL
HOT DRY ROCK
GEOPRESSURED
MAGMA
EXPLORATION
EXTRACTION
DRILLING
PRODUCTION
USES
ELECTRICITY PRODUCTION
NONELECTRIC UTILIZATIONS
• DRY STEAM
• FLASHED STEAM
• BINARY CYCLE
• HYBRID
• TOTAL FLOW
• SPACE AND DISTRICT HEATING/COOLING
• AGRICULTURAL HEATING AND IRRIGATION
• INDUSTRIAL PROCESS HEAT AND STEAM
• MINERAL AND GAS EXTRACTION

Figure 8-1. Geothermal Energy Development

8.2 SUMMARY

The input requirements and outputs associated with each phase of the geothermal energy resource development system are summarized in Tables 8-1 through 8-4. The input requirements include manpower, materials and equipment, economics, water, land, and ancillary energy. The outputs include air, water, and solid waste emissions, noise, odors, and occupational safety and health.

These summary tables present typical values for various geothermal energy development options. The inputs and outputs are based on little actual experience and should be interpreted only as preliminary estimates. These inputs and outputs vary over a wide range, depending on the characteristics of the geothermal resource and the development technology. The assumptions used to develop these tables are described in detail in their respective sections of the text.

TABLE 8-1. SUMMARY OF INPUTS AND OUTPUTS OF AN EXPLORATION EFFORT INTENDED TO DISCOVER A FIELD SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER

Input Requirements	
Manpower	
• first year	15 man-years
• second year	21 man-years
Materials and Equipment	Not quantified
Economics	$13 million[a]
Water	55 acre-feet
Land	
• temporary	19 acres
• permanent	less than 1 acre
Ancillary energy	1,700,000 gal. diesel fuel
Outputs	
Air emissions[b]	
• steam	355,000 tons
• carbon dioxide	21,000 tons
• carbon monoxide	87 tons
• hydrocarbons	210 tons
• nitrogen oxides	400 tons
• aldehydes	6 tons
• sulfur oxides	27 tons
• particulates	greater than 29 tons
• ammonia	250 tons
• hydrogen sulfide	180 tons
• nitrogen and argon	110 tons
• hydrogen	35 tons

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[a] 1975 dollars

[b] Over 18 months.

(Continued)

TABLE 8-1. SUMMARY OF INPUTS AND OUTPUTS OF AN EXPLORATION EFFORT INTENDED TO DISCOVER A FIELD SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER (CONTINUED)

Water effluents	
• drilling mud	58 acre-feet
• geothermal fluids	112 acre-feet
Solid wastes	
• drill cuttings	2 acre-feet
Noise pollution	
• well cleaning	118 db(A)[c]
Occupational health and safety	data unavailable
Odors	H_2S NH_3

[c] 50 ft. distance

TABLE 8-2. SUMMARY OF INPUTS AND OUTPUTS OF DRILLING WELLS SUFFICIENT FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER

	Hot Water/Binary Cycle	Hot Water/Steam Flashing Cycle	Hot Rock/Binary Cycle	Dry Steam/Direct Use
Input Requirements				
Manpower				
• first year	150	170	17	31-40[a]
• second year	29	32	3	6-8 [a]
Materials				
• steel	18,000 tons	20,000 tons	2,000 tons	15,000-20,000 tons[b]
Economics	$43 million[c]	$47 million[c]	$13 million[c]	$20-26 million[d,e] $80-106 million[f]
Water	290 acre-ft	310 acre-ft	32 acre-ft	58-75 acre-ft[e] 230-310 acre-ft[f]
Land				
• temporarily disturbed	98 acres	108 acres	11 acres	20-26 acres[e] 80-106 acres[f]
• required for well spacing	990-4000 acres	1100-4300 acres	110-440 acres	800-1000 acres[e] 3200-4200 acres[f]
Ancillary Energy	8.9 MM gal diesel fuel	9.7 MM gal diesel fuel	1 MM gal diesel fuel	1.8-2.3 MM gal diesel fuel[e] 7.2-9.5 MM gal diesel fuel[f]
Outputs				
Air Emissions				
• diesel generators				
carbon monoxide	450 tons	490 tons	50 tons	92-120 tons[e] 370-480 tons[e]
hydrocarbons	170 tons	180 tons	19 tons	34-43 tons[e] 130-180 tons[f]
nitrogen oxides	2100 tons	2300 tons	230 tons	420-540 tons[e] 1700-2200 tons[f]
aldehydes	31 tons	34 tons	3.5 tons	6.3-8.1 tons[e] 25-33 tons[f]
sulfur oxides	140 tons	150 tons	15 tons	28-36 tons[e] 110-150 tons[f]
particulates	150 tons	160 tons	17 tons	30-39 tons[e] 120-160 tons[f]
carbon dioxide	96,000 tons	100,000 tons	11,000 tons	19,000-25,000 tons[e] 78,000-100,000 tons[f]

(Continued)

TABLE 8-2. SUMMARY OF INPUTS AND OUTPUTS OF DRILLING WELLS SUFFICIENT FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER (CONTINUED)

	Hot Water/Binary Cycle	Hot Water/Steam Flashing Cycle	Hot Rock/Binary Cycle	Dry Steam/Direct Use
• from geothermal fluids[g]				
steam	1,330,000 tons	1,330,000 tons	--	1,330,000 tons
carbon dioxide	10,600 tons	10,600 tons	--	10,600 tons
ammonia	940 tons	940 tons	--	940 tons
methane	670 tons	670 tons	--	670 tons
hydrogen sulfide	670 tons	670 tons	--	670 tons
nitrogen and argon	400 tons	400 tons	--	400 tons
hydrogen	130 tons	130 tons	--	130 tons
Water Effluents				
• drilling mud	300 acre-ft	320 acre-ft	33 acre-ft	60-78 acre-ft[e] 240-320 acre-ft[f]
• geothermal fluids	1500 acre-ft	1700 acre-ft	--	--
Solid Wastes				
• drill cuttings	10 acre-ft	11 acre-ft	1 acre-ft	2-3 acre-ft[e] 8-11 acre-ft[f]
Noise Pollution				
• blowouts (infrequent)	118 dB(A)	118 dB(A)	--	118 dB(A)
• well-bleeding (open hole)	86 dB(A)	86 dB(A)	--	86 dB(A)
Occupational Health and Safety	Not Quantified	Not Quantified	Not Quantified	Not Quantified
Odors	H_2S NH_3	H_2S NH_3	Unknown	H_2S NH

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[a] Does not include annual drilling manpower requirements.

[b] Over 30 year life.

[c] 1976 dollars.

[d] 1977 dollars.

[e] Initial.

[f] Over 30 years; includes depletion.

[g] Based on The Geysers.

TABLE 8-3. SUMMARY OF INPUTS AND OUTPUTS ASSOCIATED WITH WELLHEAD PRODUCTION SYSTEM AT A 100 MW_e POWER PLANT

	Hot Water/Binary Fluid	Hot Water/Steam Flashing	Hot Rock/Binary Fluid	Dry Steam/Direct Use
Input Requirements				
Manpower				
• construction	30 man-years	33 man-years	3 man-years	11-14 man-years[a] 43-58 man-years[b]
• operating	3 men	3 men	0.3 men	~1.2 men
Materials				
• steel	2,700 tons	3,000 tons	430 tons	950-1300 tons[a] 3900-5300 tons[b]
Economics	$12 million	$13 million	$1.8 million	$6.1-$8 million[a] $37-$50 million[b]
Water	--	--	2.5-5 acre-ft/d	--
Land	28 acres	30 acres	3 acres	9-13 acres[a] 39-53 acres[b]
Ancillary Energy	None-Variable	None-Variable	Variable	None-Variable
Outputs				
Air Emissions	Small	Small	Small	Small
Water Effluents	Small	Small	Small	Small
Solid Wastes	Undetermined	Undetermined	Undetermined	Undetermined
Noise Pollution				
• production	Little	Little	Little	Little
• muffled vent[c]	90 db(A)	90 db(A)	90 db(A)	90 db(A)
Occupational Health and Safety	Not Quantified	Not Quantified	Not Quantified	Not Quantified
Odor	NH_3 H_2S	NH_3 H_2S	Unknown	NH_3 H_2S

[a] Initial [b] Over 30 years [c] At 90 feet

TABLE 8-4. SUMMARY OF INPUTS AND OUTPUTS OF A GEOTHERMAL POWER PLANT PRODUCING 100 MW_e

	Hot Water/Binary Fluid	Hot Water/Steam Flashing	Hot Rock/Binary Fluid	Dry Steam/Direct Use
Input Requirement				
Manpower				
• construction	257 man-years	260 man-years	230 man-years	170 man-years
• operating	28 men	28 men	26 men	8 men
Materials				
• steel in piping network	2200 tons	2400 tons	360 tons	40 tons
Economics				
• capital costs[a]	$66.4 million	$131.4 million	$40.9 million	—
• power generation costs[b]	3.1¢/kWh[c]	4.7¢/kWh[c]	1.6¢/kWh[c]	2.0¢/KWh[d]
Water				
• total make-up	13,000 acre-ft/yr[e]	13,000 acre-ft/yr[e]	13,000 acre-ft/yr[e]	None
Land	31 acres	37 acres	15 acres	4 acres
Ancillary Energy	None	None	None	None
Outputs				
Air Emissions				
• carbon dioxide	Unknown	Unknown	Unknown	5500 lb/hr
• hydrogen sulfide				380 lb/hr
• methane				330 lb/hr
• hydrogen				80 lb/hr
• ammonia				330 lb/hr
• arsenic				0.01 lb/d
• boron				21 lb/d
• mercury				0.0006 lb/d
Water Effluents				
• blowdown	3,000 acre-ft/yr	3,000 acre-ft/yr	3,000 acre-ft/yr	1,100 acre-ft/yr
• spent brine	51,000 acre-ft/yr	52,000 acre-ft/yr	20,000 acre-ft/yr	—
Solid Wastes	Not Quantified	Not Quantified	Not Quantified	Not Quantified
Noise Pollution	90 dB(A)	90 dB(A)	90 dB(A)	90 dB(A)
Occupational Health and Safety	Not Quantified	Not Quantified	Not Quantified	Not Quantified
Odors	NH_3 H_2S	NH_3 H_2S	Unknown	NH_3 H_2S

[a] Based on 150 C resource. [b] Including capital charge. [c] 1976 dollars. [d] 1977 dollars. [e] Complete reinjection of geothermal fluids.

8.3 RESOURCE CHARACTERISTICS

Geothermal resources are usually defined as "reserves of heat relatively near the earth's surface, created by the underlying geologic structure of the earth."[1] This section discusses the geology, location, quantity, physical and chemical characteristics, and ownership of geothermal resources.

8.3.1 Geology

Geothermal energy is derived from the decay of radioactive elements (chiefly uranium and thorium), friction (tidal and crustal plate motion), and possibly primeval heat. The heat is transferred radially outward, mainly by convection with the ascent of magma in the crust and upper mantle. In the uppermost part of the crust, convection in deep groundwater transports heat to the surface. In the crust, most of the earth's heat is transferred to the surface by conduction through solid rock.[2,3,4]

The geothermal resource base, defined as the total amount of heat stored in the outer ten kilometers of the earth, has been calculated to be 1×10^{24} Btu.[1] However, because the heat is diffuse, only a small fraction of that amount is recoverable.[2] Locally, the heat is concentrated in the crust by volcanism, tectonism, and convection cells of circulating hot waters above buried magma chambers. The heat is stored in rocks and in water and steam within pores and fissures.[3] These "geothermal reservoirs" may be defined geologically as hydrothermal convection, hot igneous, and conduction-dominated systems.[4]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 3.

[2] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, pp. 3-4.

[3] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973, p. II-10.

[4] Resource Planning Associates, Inc., *op.cit.*, p. 33.

8.3.1.1 Hydrothermal Convection Systems

Subsurface reservoirs of steam or hot liquid water are categorized as hydrothermal convection systems. As shown in Figure 8-2, a heat source of hot rock or magma that lies relatively close to the earth's surface (usually at depths of 2 to 8 km) is overlain by a permeable rock formation containing water. The hot rock or magma transfers heat to the water circulating in the permeable formation. The water expands and rises upward as it is heated by the hot rock or magma below. Above the permeable rock is a layer of impermeable rock which traps the hot water. If the impermeable layer contains cracks or fissures through which fluid can rise, the

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[1] White, D. E. and D. L. Williams. "Summary and Conclusions," Assessment of Geothermal Resources of the United States - 1975. Geological Survey Circular 726. Arlington, VA: U.S. Geological Survey, 1975, p. 147.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 3.

[3] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973, p. II-10.

[4] Resource Planning Associates, Inc., *op.cit.*

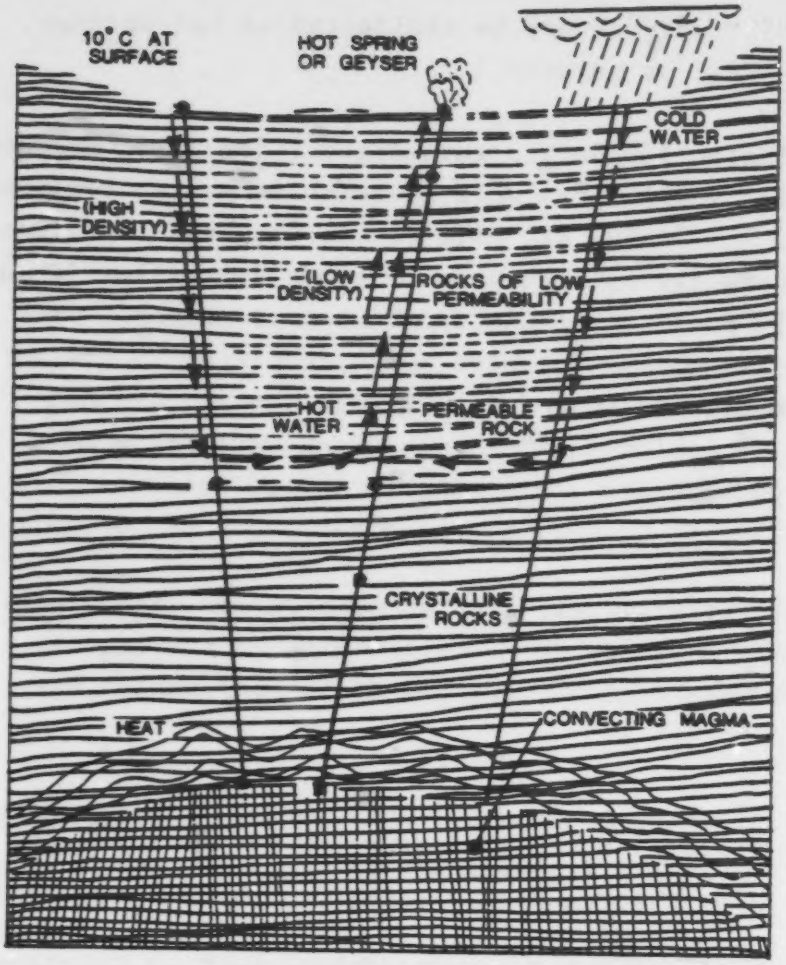
10°C AT SURFACE
HOT SPRING OR GEYSER
COLD WATER
(HIGH DENSITY)
(LOW DENSITY)
ROCKS OF LOW PERMEABILITY
HOT WATER
PERMEABLE ROCK
CRYSTALLINE ROCKS
HEAT
CONVECTING MAGMA

Figure 8-2. Structure of a Typical Hydrothermal Convection System

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Source: Austin, A. L. (1974, p. 15). As reproduced in: Western Energy Resources and the Environment: Geothermal Energy. Resource Planning Associates. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency. May 1977.

hot fluid will emerge as steam (a vapor-dominated system) or hot liquid water (a liquid-dominated system).[1] On the surface, the hydrothermal reservoir may be manifested as hot springs, fumaroles, mud pots, or geysers.[2]

Vapor-dominated fluids are advantageous for power production because they are usually available at relatively high temperature and pressure (*e.g.*, 180°C, 114 psia at the Geysers[3,4]). Since the steam contains few particulates or other impurities it can be used directly to drive conventional steam turbines. Only three vapor-dominated systems have been identified in the United States: The Geysers in Sonoma County, California; the Mud Volcano system in Yellowstone National Park, Wyoming; and a likely though unconfirmed system in Mt. Lassen National Park, California. Only the Geysers has been developed commercially.[5]

Liquid-dominated systems are far more common than vapor-dominated systems: worldwide, liquid-dominated systems may be twenty times more common.[6] Liquid-dominated systems are usually classed as:

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 11.

[2] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 4.

[3] Hansen, A. "Thermal Cycles for Geothermal Sites and Turbine Installation at the Geysers Power Plant, California." Geothermal Energy, Proceedings of U.N. Conference on New Sources of Energy. Rome: August 21-31, 1961, pp. 365-379.

[4] Kruger, P. and C. Otte, eds. Geothermal Energy. Stanford, CA: Stanford University Press, 1973.

[5] Resource Planning Associates, Inc., *op.cit.*, p. 15.

[6] The Futures Group, *op.cit.*

1. High temperature systems, with temperatures in excess of 150°C;

2. Intermediate temperature systems, with temperatures ranging from 90°C to 150°C; and

3. Low temperature systems, with temperatures less than 90°C.[1]

Only the high temperature system is currently being considered for electricity generation. Moderate and low temperature systems are more suitable for direct thermal or other nonelectric purposes. Nine electricity generating plants have been developed based on high-temperature hot water systems. Most of these plants are located in New Zealand, Japan, and Mexico.[2] Nonelectric utilizations exist in Iceland, Japan, the Soviet Union, Hungary, France, Italy and the United States. Hot water plants at Roosevelt Hot Springs, Utah and Valles Caldera, New Mexico will be operating by 1982.

8.3.1.2 Hot Igneous Systems

Hot igneous systems include both magma (molten rock) at temperatures above 650°C and hot dry rocks at temperatures below 650°C. Magma systems contain more stored heat per unit volume than other geothermal systems. However, many characteristics of the magma resource are largely unknown and the technology required for commercial use of the resource is undeveloped. Large young magma systems are especially attractive for future exploration and development.[1,2]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 16.

[2] *Ibid.*, pp. 16, 18.

Hot dry rock systems overlie a local heat source such as a magma chamber. The rock formations in these systems are not sufficiently permeable to trap water. Consequently, production requires: 1) creating underground cavities by explosion or creating large cracks in the rock formation by fracturing with cold water;[3] 2) injecting water to absorb the heat from the rock; and 3) collecting the hot water or steam subsequently produced. The Los Alamos Scientific Laboratory has successfully fractured hot rock at Fenton Hill, NM. Eighty-five percent of the water injected into the formation was recovered at 130°C. A thermal loop extracting 10 MW of thermal energy is now operating.[4] Commercial utilization of the hot dry rock resource is not expected until the late 1980's.[5]

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[1] White, D. E. and D. L. Williams, eds. Assessment of Geothermal Resources of the United States - 1975. Geological Survey Circular 726. Arlington, VA: U.S. Geological Survey, 1975, pp. 1-3.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 28.

[3] Fracturing is unnecessary if the only deficiency is in water rather than permeability.

[4] Mortensen, J. J. "The LASL Hot Dry Rock Geothermal Energy Development Project." LASL Mini-Review. July 1977.

[5] LaMori, P. "Geothermal Research and Advanced Technology." Energy Technology III: Commercialization. R. F. Hill (ed.). Washington, D.C.: Government Institutes, Inc., 1976, p. 114.

8.3.1.3 Conduction-Dominated Systems

Conduction-dominated systems have been described by Resource Planning Associates:[1]

> Where conduction is dominant, a temperature gradient exists within the earth such that temperatures increase proportionally with depth from the surface at a constant rate. This temperature gradient, or rate of heat flow, may be increased or decreased by the presence of fluids or low-conductivity rocks. The heat content is unrelated to plate tectonics. Both of the geothermal resources in this category are conduction-dominated systems, referred to as the normal gradient and geopressured geothermal reservoirs.

The normal gradient refers to the flow of heat from regional conductive environments. Given the steady flow of heat, temperatures of 75°C may exist at a depth of about 3 km.[2] Heat from these regional conductive environments is likely to be developed via the same technology used to recover heat from hot igneous systems.

Geopressured zones occur throughout the world in basins where rapid sedimentation and contemporary faulting have occurred, and are characterized by abnormally high pressures and temperatures.[3] Geopressured reservoirs in the United States comprise methane-saturated water contained in layers of sand

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 33.

[2] *Ibid.*, pp. 33-34.

[3] Wilson, J. S., et al. Environmental Assessment of Geopressured Waters and Their Projected Uses. Dow Chemical U.S.A. Prepared for U.S. Environmental Protection Agency, Contract No. 68-02-1329. April 1977, p. 10.

and shale beneath impermeable rock. Geopressured waters containing methane can supply three kinds of energy: thermal, from the water, which typically has temperatures from 160°C to 200°C; mechanical or hydraulic, from the high pressures present in the formation; and fuel, from the water, which may contain a large quantity of methane. In the United States, these geopressured zones occur along the Texas and Louisiana Gulf Coast, extending out to the Continental Shelf.[1] Development is 5 to 15 years in the future.[2] Geopressured zones are not known to occur in the eight western states studied in this report.

8.3.2 Location

Figure 8-3 is a map of known high-temperature U.S. geothermal regions, including the geopressured zone of the Gulf Coast.[3] In the U.S., most locations likely to be developed before 1985 (and probably by 2000) are in the western one-third of the country. There are currently 441 identified geothermal resource areas in the U.S.[4] Figure 8-4 shows the location of the identified geothermal resource regions in the eight western states studied in this report. A known geothermal resource area (KGRA)

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 34.

[2] Wilson, J. S., et al. Environmental Assessment of Geopressured Waters and Their Projected Uses. Dow Chemical U.S.A. Prepared for U.S. Environmental Protection Agency, Contract No. 68-02-1329. April 1977. p. iv.

[3] Low-temperature regions not shown in Figure 8-3 (such as the Madison aquifer) may be used as a source of low grade heat.

[4] White, D. E. and D. L. Williams, eds. Assessment of Geothermal Resources of the United States - 1975. Geological Survey Circular 726. Arlington, VA: U.S. Geological Survey, 1975, pp. 8-50, 63-77.

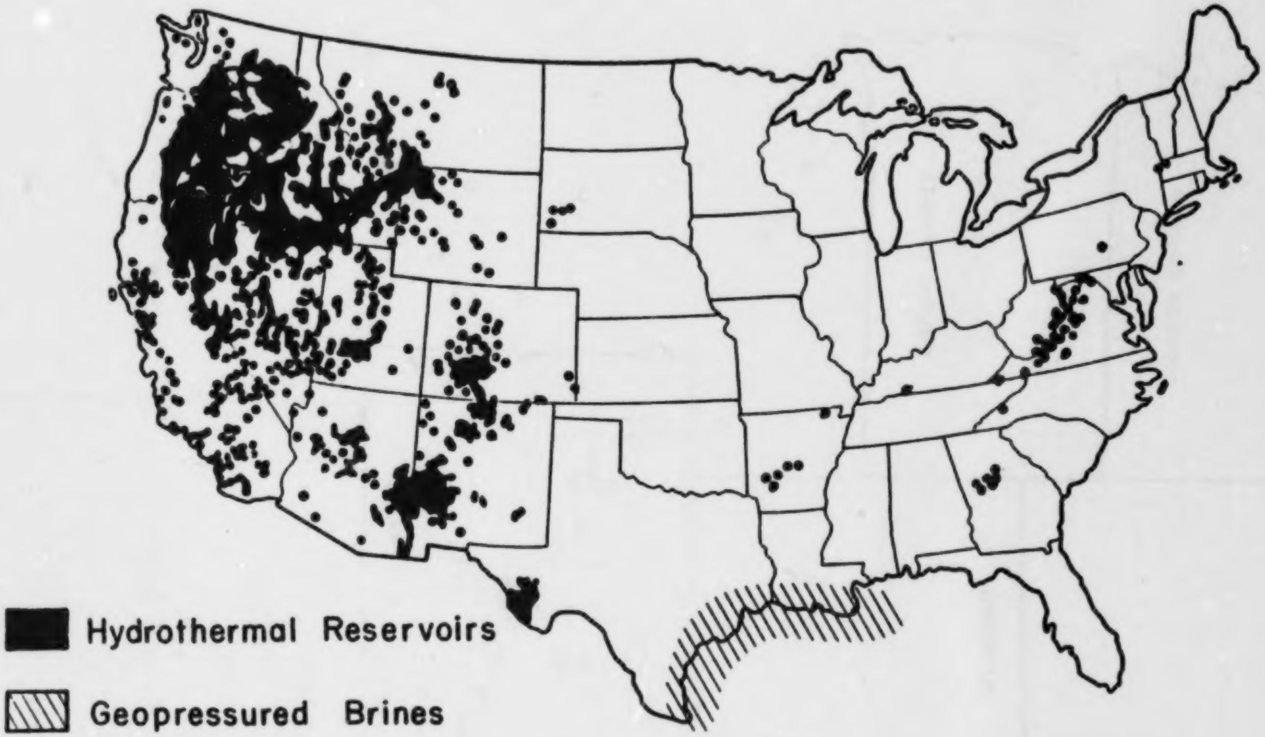
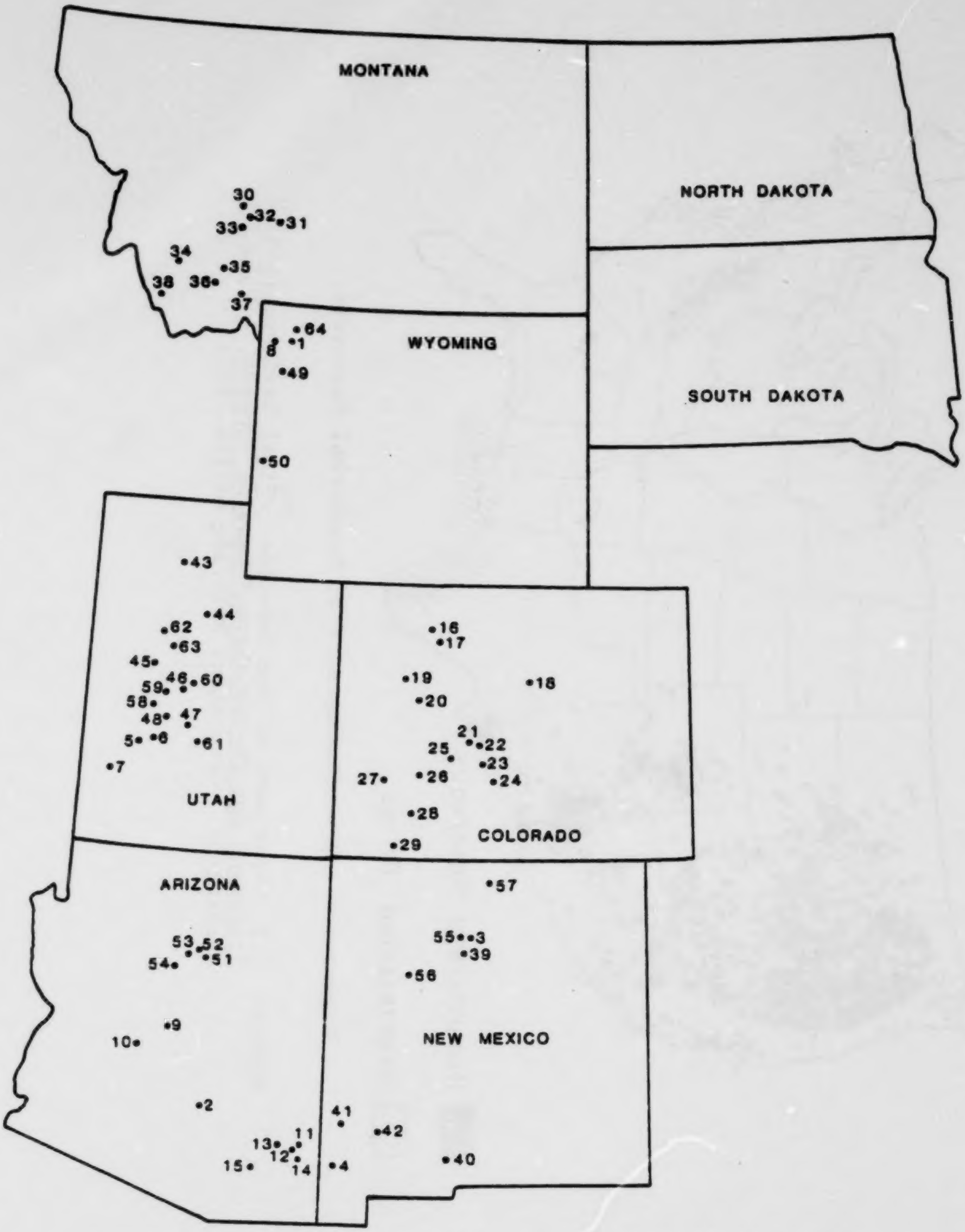

Hydrothermal Reservoirs
Geopressured Brines

Figure 8-3. Distribution of U.S. Geothermal Resources.

Source: U.S. Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program, 4 Vols. Washington: Government Printing Office, 1973.


MONTANA
NORTH DAKOTA
SOUTH DAKOTA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
30
32
31
33
34
35
38
36
37
64
1
8
49
50
43
44
62
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51
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2
41
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42
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4
40

Figure 8-4. The Location of Known Geothermal Resource Areas in the Eight Western States

KEY TO FIGURE 8-4

Map Number	Name-Site	State
	Vapor-Dominated (Steam) Systems	
1.	Mud Volcano System Yellowstone National Park	Wyoming
	High-Temperature Hot-Water Systems (Over 150°C)	
2.	Power Ranch Wells	Arizona
3.	Valles Caldera	New Mexico
4.	Lightning Dock Area	New Mexico
5.	Roosevelt (McKean) H.S.	Utah
6.	Cove Fort-Sulphurdale	Utah
7.	Thermo H.S.	Utah
8.	Yellowstone National Park	Wyoming
	Intermediate-Temperature Hot-Water Systems (90° to 150°C)	
9.	Verde H.S.	Arizona
10.	Castle H.S.	"
11.	North of Clifton	"
12.	Clifton H.S.	"
13.	Eagle Creek Springs	"
14.	Gillard H.S.	"
15.	Mt. Graham	"
16.	Routt H.S.	Colorado
17.	Steamboat Springs	"
18.	Idaho Springs	"
19.	Glenwood Springs	"
20.	Avalanche Springs	"
21.	Cottonwood Springs	"
22.	Mt. Princeton S.	"
23.	Poncha H.S.	"
24.	Mineral H.S.	"
25.	Waunita H.S.	"
26.	Cebolla H.S.	"
27.	Orvis H.S.	"
28.	Wagon Wheel Gap	"
29.	Pagosa H.S.	"
30.	Helena (Broadwater) Hot Spring	Montana
31.	White Sulphur Springs	"
32.	Alhambra H.S.	"
33.	Boulder H.S.	"
34.	Gregson (Fairmont) H.S.	"
35.	Pipestone H.S.	"

KEY TO FIGURE 8-4 (Continued)

Map Number	Name-Site	State
36.	Barkels (Silver Star) H.S.	Montana
37.	Norris (Hapgood) H.S.	"
38.	Jardine (Big Hole or Jackson) H.S.	"
39.	Jemez (Ojos Calientes) H.S.	New Mexico
40.	Radium H.S.	"
41.	Lower Frisco	"
42.	Gila H.S.	"
43.	Hooper H.S.	Utah
44.	Crystal H.S.	"
45.	Baker (Abraham, Crater) H.S.	"
46.	Meadow H.S.	"
47.	Monroe (Cooper) H.S.	"
48.	Joseph H.S.	"
49.	Huckleberry H.S.	Wyoming
50.	Auburn H.S.	"
	Hot Igneous (Volcanic) Systems	
51.	San Francisco Mountains	Arizona
52.	Kendrick Peak	"
53.	Sitgreaves Peak	"
54.	Bill Williams Mountain	"
55.	Valles Caldera	New Mexico
56.	Mount Taylor	"
57.	No Agua Domes	"
58.	Mineral Mountains	Utah
59.	Cove Creek Domes	"
60.	White Mountain Rhyolite	"
61.	Tushar Mountains	"
62.	Topaz Mountain	"
63.	Smelter Knoll	"
64.	Yellowstone Caldera System	Wyoming

Source: White, D. E. and D. L. Williams, eds. Assessment of Geothermal Resources of the United States - 1975. Geological Survey Circular 726. Washington: U.S. Geological Survey, 1975, pp. 8-5, 53-77.

occurs when "the prospect of extraction of geothermal steam or associated geothermal resource from an area is good enough to warrant expenditure of money for that purpose."[1] KGRA's also are designated when applications for non-competitive leases overlap in an area. As evident from Figure 8-4, there are currently 64 KGRA's in the study area: 9 in Montana, 5 in Wyoming, 15 in Utah, 14 in Colorado, 12 in Arizona, and 9 in New Mexico. There are no KGRA's in North and South Dakota.[2] Areas not shown in Figure 8-4 may be sufficient to supply low grade heat for various non-electric uses.

8.3.3 Quantity

Estimates of the total geothermal energy resource base of the United States have been reported by Muffler and White[3] (1972), White[4] (1973), Rex and Howell[5] (1973), and more recently, by White and Williams[6] (1975). These estimates vary widely due to the uncertain characteristics of the geothermal energy resource.

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[1] Godwin, L. H., et al. Classification of Public Lands Valuable for Geothermal Steam and Associated Geothermal Resources. USGS Circular 647. Washington: Government Printing Office, 1971, p. 2.

[2] White, D. E. and D. L. Williams, eds. Assessment of Geothermal Resources of the United States - 1975. Geological Survey Circular 726. Arlington, VA: U.S. Geological Survey, 1975.

[3] Muffler, L. and D. White. Geothermal Energy Resources of the U.S. U.S. Geological Survey Circular 650. Washington: Government Printing Office, 1972.

[4] White, D. E. "Characteristics of Geothermal Resources," Geothermal Energy: Resources, Production, Stimulation. P. Kruger and C. Otte (eds.). Stanford, CA: Stanford University Press, 1973, pp. 69-94.

[5] Rex, R. W. and D. J. Howell. "Assessment of U.S. Geothermal Resources," Geothermal Energy: Resources, Production, Stimulation. P. Kruger and C. Otte (eds.). Stanford, CA: Stanford University Press, 1973, pp. 59-68.

[6] White, D. E. and D. L. Williams, eds., *op.cit.*

The resource assessment presented by White and Williams relies on data available in 1975, and is subject to revision as new information becomes available. As defined by White and Williams, the geothermal resource base includes all stored heat above 15°C to 10 km depth. Geothermal resources are defined as "the stored heat, both identified and undiscovered, that is recoverable using current or near-current technology, regardless of cost." The assessment makes no attempt to consider those legal, environmental, and institutional limitations controlling the development of geothermal resources.[1]

Three categories of geothermal resources have been established by White and Williams: 1) geothermal reserves are those identified resources recoverable at a cost that is currently competitive with the costs of other energy resources; 2) paramarginal geothermal resources are recoverable at costs between one and two times the current costs of competitive energy systems; and 3) submarginal geothermal resources are those recoverable only at costs greater than two times the costs of competitive energy.[2] Distinctions between these resource categories are dependent on the prevailing costs of more conventional energy resources. The distinction between resource base and resources is dependent on the current state of geothermal technology.

The estimated heat content of the geothermal resource base of the United States, as summarized by White and Williams, is reported in Table 8-5. Although the hot igneous and conduction-dominated systems constitute the greatest portion of the world's geothermal resource base, White and Williams considered recovery

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[1] White, D. E. and D. L. Williams. "Summary and Conclusions," Assessment of Geothermal Resources of the United States - 1975. Geological Survey Circular 726. Arlington, VA: U.S. Geological Survey, 1975, p. 147.

[2] *Ibid.*

TABLE 8-5. ESTIMATED HEAT CONTENT OF GEOTHERMAL RESOURCE BASE OF THE UNITED STATES[a]

System Type	Identified Systems Number	Identified Systems Heat Content 10^{16} Btu	Total Resource[b] Heat Content, 10^{16} Btu
1. Hydrothermal Convection[c]			
a. Vapor-Dominated	3	10	20
b. High-Temperature Liquid Dominated[d]	63	147	630
c. Intermediate-Temperature Liquid Dominated[e]	224	137	560
TOTAL	290	~294	~1210
2. Hot Igneous			
a. Molten[f]		~5200	
b. Hot Rock[g]		~4800	
TOTAL		~10,000	~40,000
3. Conduction-Dominated[h]		~3,000,000	~3,000,000

[a] Heat in ground, without regard to recoverability. Estimates include all stored heat above 15°C to 10 km depth.

[b] Includes both identified and estimated undiscovered resource.

[c] To 3 km (10,000 ft) depth, near the maximum drilled in geothermal areas.

[d] Over 150°C.

[e] 90° to 150°C.

[f] Molten parts of 48 best known hot igneous systems, including Alaska and Hawaii.

[g] Crystallized parts and hot margins of 48 best known hot igneous systems.

[h] Includes geopressured reservoirs.

Source: White, D. E. and D. L. Williams. "Summary and Conclusions", Assessment of Geothermal Resources of the United States-1975. Geological Survey Circular 726. Arlington, VA: U.S. Geological Survey, 1975 p.148.

technologies for these systems to be relatively undeveloped.[1] As discussed earlier, commercial development technologies for these resource systems may be available by the late 1980's. The identified geothermal resource areas of the eight states in this technology assessment are described in Table 8-6.

Estimates of the near-term development potential of geothermal resources vary widely, depending on the assumptions used. One view holds that geothermal energy is most important for electricity generation, but only in certain local areas or in undeveloped countries seeking alternatives to even more expensive energy sources. The counterview holds that geothermal energy has the greatest potential in non-electric applications.[2]

The projections of various studies on the potential of geothermal energy as a source of electricity are shown in Table 8-7. Differences among these projections are attributed to different expectations of future technological breakthroughs, information on resource characteristics, and future costs of alternate energy sources.[3] The most recent projection of the commercial utilization of geothermal energy is reproduced in Table 8-8.

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[1] White, D. E. and D. L. Williams. "Summary and Conclusions," Assessment of Geothermal Resources of the United States - 1975. Geological Survey Circular 726. Arlington, VA: U.S. Geological Survey, 1975, p. 154.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 3

[3] *Ibid.*, p. 5.

TABLE 8-6. IDENTIFIED GEOTHERMAL AREAS OF THE EIGHT WESTERN STATES

	State								
	Arizona	Colorado	Montana	New Mexico	North Dakota	South Dakota	Utah	Wyoming	Total
Vapor Dominated Systems									
Number of Areas	0	0	0	0	0	0	0	1	1
Assumed Subsurface Area, km^2	—	-	-	-	-	-	-	5	5
Assumed Heat Content, 10^{18} Btu[a]	—	-	-	-	-	-	-	-0.3	~0.3
High-Temperature Liquid-Dominated Systems (over 150°C)									
Number of Areas	1	0	0	2	0	0	3	1	7
Assumed Subsurface Area, km^2	-2.5	-	-	66.5	-	-	20.5	375	465
Assumed Heat Content, 10^{18} Btu[a]	0.1	-	-	-7	-	-	~1.5	~53	~62
Intermediate-temperature Liquid-Dominate Systems (90°C to 150°C)									
Number of Areas	7	14	9	4	0	0	6	2	42
Assumed Subsurface Area, km^2	10.5	27.0	13.5	6.0	-	-	12.5	3.0	73
Assumed Heat Content, 10 Btu	~0.4	~1.2	~0.6	~0.3	-	-	~0.5	~0.2	~3.2
Hot Igneous Systems									
Number of Areas	4	0	0	3	0	0	6	1	14
Assumed Subsurface Area, km^2	250[b]	-	-	400[b]	-	-	104[c]	2500	3250
Assumed Heat Content, 10^{18}Btu[a]	125[b]	-	-	160	-	-		~750	-1035

[a] Heat contents calculated above a base temperature of 15°C

[b] Data given for one identified area only.

[c] Data given for two identified areas only.

Source: White, D. E. and D. L. Williams, eds. Assessment of Geothermal Resources of the United States-1975. Geological Survey Circular 726.

Arlington, VA: U.S. Geological Survey, 1975. pp. 8-72.

TABLE 8-7. PROJECTIONS OF ELECTRICITY GENERATING CAPACITY FROM GEOTHERMAL RESOURCES IN THE UNITED STATES, 1985-2000

Source of Projections	Projected Capacity, MW_e 1985	2000
Energy Resource Conference, 1975	2,500 to 5,100	-
ERDA-86, Geothermal Energy Definition Report, 1975	6,000	39,000
Electric Power Research Institute, 1976	3,500	10,000
National Electric Reliability Council, 1976	2,080	-
ERDA, Program Approval Document, 1977	3,000-4,000	20,000-40,000

Sources: Loveland, W. D., B. I. Spinrad, and C. H. Wang, eds. "Magnitude and Development Schedule of Energy Resources." Proceedings of a conference held in Portland, July 1975. Oregon State University, Corvallis, September 1975.

U.S. Energy Research and Development Administration. Definition Report, Geothermal Energy Research, Development and Demonstration Program. ERDA-86. Washington D.C., October, 1975.

U.S. Energy Research and Development Administration. Program Approval Document, Geothermal Energy Development, Fiscal Year 1977. January 17, 1977

National Electric Reliability Council. "Fossil and Nuclear Fuel for Electric Utility Generation, Requirements and Constraints 1976-1985." June, 1976.

Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington D.C.: U.S. Environmental Protection Agency, May 1977.

TABLE 8-8. INTENDED COMMERCIAL DEVELOPMENT OF GEOTHERMAL ENERGY GIVEN SUCCESSFUL IMPLEMENTATION OF FEDERAL PROGRAM

	1985	2000	2020
Electric Capacity, MW_e	3,000-4,000	20,000-40,000	70,000-140,000
Electric Applications -			
Equivalent Fossil Fuel Energy, quads/year	0.2-0.3	1.5-3.0	5-10
Nonelectric Applications, quads/year	0.1	1	8
TOTAL, quads/year	0.3-0.4	2.5-4.0	13-18

Note: 1 quad = 10^{15} Btu

Source: U.S. Energy Research and Development Administration. Program Approval Document, Geothermal Energy Development, Fiscal Year 1977. January 17, 1977.

By 1985, electricity generating capacity from geothermal resources is likely to amount to 2000-4000 MW_e.[1,2,3] Total U.S. generating capacity in 1985 has been forecasted as 800,000 MW_e.[4] Geothermal electric generating capacity will thus amount to only 0.25 to 0.50% of the total generating capacity in the U.S. By 2000, geothermal electric generating capacity will amount to 10,000-40,000 MW_e.[5,6] If the total generating capacity in 2000 amounts to about two million MW_e[7], geothermal electric generating capacity will comprise 0.50 to 2.0% of the total generating capacity in the United States.

8.3.4 Physical and Chemical Characteristics

The ranges of concentrations of the various chemicals in geothermal fluids are shown in Figure 8-5. As evident from Figure 8-5, concentrations of constituent chemicals in geothermal

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[1] National Electric Reliability Council. "Fossil and Nuclear Fuel for Electric Utility Generation, Requirements and Constraints 1976-1985." June 1976.

[2] U.S. Energy Research and Development Administration. Program Approval Document, Geothermal Energy Development, Fiscal Year 1977. January 17, 1977. p. 3.

[3] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 3.

[4] National Electric Reliability Council, *op.cit.*

[5] Resource Planning Associates, Inc., *op.cit.*

[6] U.S. Energy Research and Development Administration, *op.cit.*

[7] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975.

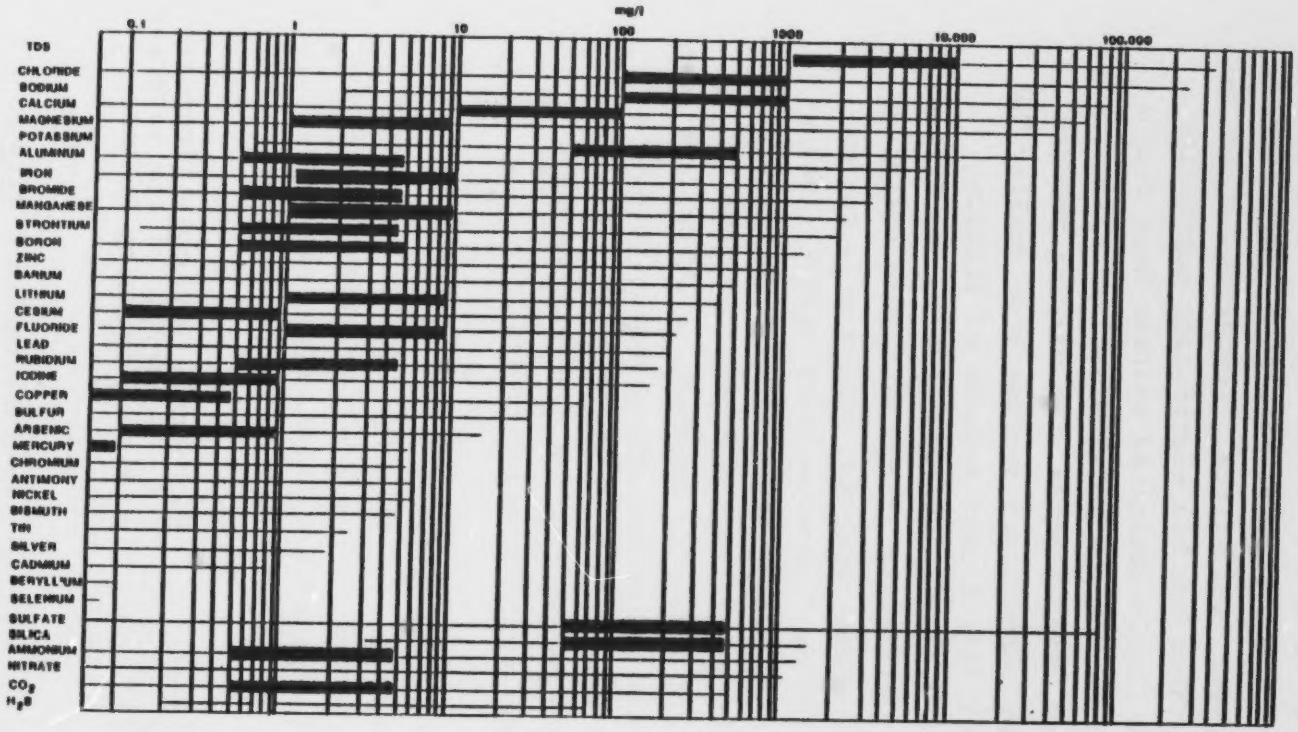

Figure 8-5. Ranges of Chemical Constituent Concentrations in Geothermal Fluids, MG/L.

Note: Narrow bars show measured ranges. Wide bars show ranges within which median concentrations will likely fall. Where no wide bar is shown, data are insufficient to make judgments as to median concentrations. Graph prepared by R. P. Hartley, Program Manager for Geothermal Energy, Energy Systems Environmental Control Division, U.S. EPA, Industrial Environmental Research Laboratory.

Source: Douglas, J. D., R. J. Serne, D. W. Shannon, E. M. Woodruff. Geothermal Water and Gas - Collected Methods for Sampling and Analysis. BNWL-2094, Battelle-Pacific Northwest Laboratories, August 1976.

Cosner, S. R. Geothermal Brine Data File (Revised). Lawrence Berkeley Laboratory, University of California. February 3, 1977.

S. K. Sanyal. Preliminary Compilation of Chemical Composition of Geothermal Waters. Geonomics, Inc.

fluids vary widely from site to site. Chief chemical constituents of geothermal fluids are sodium, calcium, potassium, magnesium, chloride, sulfate, bicarbonate, and silica. Geothermal steam at the Geysers has few of these but has significant quantities of associated gases. Many liquid-dominated systems have fluids averaging between 2000 and 20,000 ppm total dissolved solids, principally sodium, calcium, and chloride with varying amounts of other constituents. Low temperature systems have smaller TDS concentrations. Lesser but significant amounts of lithium, boron, fluoride and nitrogen dioxide are also found. At Niland, in the Imperial Valley in California, total dissolved solids of 250,000 ppm and higher have been reported, principally sodium, calcium, potassium and chloride. Various heavy metals, such as iron, manganese, copper, zinc, lead, and strontium have also been found at Niland in concentrations ranging from a few tens to several hundred ppm, and are likely to be found at other locations. A few ppm of iron, manganese, aluminum, and arsenic are also typically present in high-temperature liquid-dominated fields. Dissolved gases may include oxygen, carbon dioxide, hydrogen sulfide, methane, hydrogen, ammonia, and nitrogen.[1]

Because of industrial proprietary information rights, chemical analyses are generally unavailable for most geothermal reservoirs in the United States.[2] The U.S. Geological Survey is currently updating and expanding a computerized geothermal data file (GEOTHERM).[3,4] An ERDA (Lawrence Berkeley Laboratory) program begun in 1976 has been collecting and evaluating fluid data for resource sites in the U.S. with minimum thermal capacities of 10^{18} calories. As of November 1976, data had been collected for 13 of the 33 sites most likely to be developed by 1985. ERDA has indicated that available geothermal fluid analyses are not adequate for economic and environmental cost estimates.[1]

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 34.

[2] *Ibid.*

[3] Energy Research and Development Administration. First Annual Report, Geothermal Energy Research, Development and Demonstration Program. ERDA 77-9, April 1977, p. 20.

[4] U.S. Geological Survey. Geothermal Fluid Data File. April 1977.

Characteristics of U.S. geothermal fields at The Geysers and Niland (in California) are summarized in Table 8-9. Characteristics of fluids from a well in Sandoval County, New Mexico, are reported in Table 8-10. Characteristics of liquids from wells at Roosevelt Hot Springs in Beaver County, Utah, are summarized in Table 8-11. The characteristics reported in Tables 8-9 through 8-11 should not be construed as representative of all geothermal fluids in the U.S. or in the eight western states.

8.3.5 Ownership

Ownership of geothermal resources has not been well defined. Because land ownership comprises ownership of surface and mineral estates (as described in Chapter 2), geothermal fluids must be defined as minerals or water; water is usually classed as part of the surface estate. The dispute over ownership of geothermal resources is still being argued in the courts;[2] the U.S. Supreme Court has ruled that geothermal resources are minerals for federal purposes.[3]

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[1] Energy Research and Development Administration. First Annual Report, Geothermal Energy Research, Development and Demonstration Program. ERDA 77-9, April 1977. pp. 28-29.

[2] See Section 8.4.4.

[3] United States v. Union Oil Company of California, 549 F.2d 1271 (1977).

TABLE 8-9. CHARACTERISTICS OF TWO U.S. GEOTHERMAL FIELDS

	Geysers Vapor Dominated	Niland Liquid Dominated
Reservoir temperature, °C	245	300+
Reservoir pressure, psi	500	2,000
Wellhead pressure, psi	150	400
Heat content, Btu/lb	1,200	560
Average well depth, ft	8,200	4,250
Fluid salinity, ppm	1,000	250,000
Average mass flow per well, lb/hr	150,000	440,000
Non-condensable gases, wt.%	1	1

Sources: Koenig, J. B. "Worldwide Status of Geothermal Resources Development," Geothermal Energy: Resources, Production, Stimulation. P. Kruger and C. Otte, eds. Stanford, California: Stanford University Press, 1973, pp. 15-58

Austin, A. L., G. H. Higgens, and J. H. Howard. The Total Flow Concept for Recovery of Energy from Geothermal Hot Brine Deposits. Lawrence, California: Lawrence Livermore Laboratory, 1973.

TABLE 8-10. CHARACTERISTICS OF GEOTHERMAL FLUIDS FROM A WELL IN SANDOVAL COUNTY, NEW MEXICO[a]

Characteristics of Steam Phase	
Constituent	Concentration, ppm
CO_2	33,700-47,390
H_2S	290-567
NH_3	1.5-6
CH_4	0-6
H_2	1.5-4
N_2	0-109
Characteristics of Liquid Phase	
General Properties	
pH	6.6-7.1
Conductivity, µmhos/cm	10,630-11,230
Specific gravity	1.008
Constituent	Concentration, ppm
Metals	
Potassium	463-550
Sodium	2,010-2,200
Calcium	27-46
Si as SiO	640-835
Anions	
Bicarbonate	57-128
Carbonate	0
Chloride	3,400-4,400
Sulfide	1.5-6
Sulfate	50-70
Solids	
Suspended solids	522-688
Total dissolved solids	6,896-7,593

[a] Fluid temperature = 170°C. Sampling method: liquid separated from steam and noncondensable gases in centrifugal separator and cooled under line pressure. Steam condensed and separated from noncondensables.

Source: U.S. Geological Survey. Geothermal Fluid Data File. April 1977

TABLE 8-11. CHARACTERISTICS OF LIQUIDS FROM WELLS AT ROOSEVELT HOT SPRINGS IN BEAVER COUNTY, UTAH

	Wells			
	Phillips 54-3B	Phillips 54-3A	Phillips 9-1	Phillips 3-1
Temperature at bottom hole, °C		>260°C		>205°C
pH		6.5		6.3
Total dissolved solids, ppm		6,442		7,067
Concentration of chemical constituents, ppm				
SiO_2	775	>560	>170	560
Na	2,400	2,000	2,210	2,437
K	565	410	425	448
Li	18	19	83	20
Ca	9	10.1		8
Mg	19	0.24		0.01
Cl	4,800	3,400	2,800	4,090
Br	7			
SO_4	200	54	122	59
Ag	0.09			
As	3.5			
B	45	29		25
Co	0.15			
Cr	0.01			
Cu	0.03			
Mn	0.15			
Mo	0.04			
Ni	0.18			
Pb	0.1			
Zn	0.04			
F		5		5
NO_3		Trace		0.1
HCO_3		200		180

Source: U.S. Geological Survey. Geothermal Fluid Data File. April 1977

Estimates vary, but about 60 percent of the known geothermal resources are on land owned by the federal government.[1] Owners of the remainder have not been determined. Table 8-12 reports the status of geothermal leases on both public and Indian land in late 1976. Detailed statistics for leases let on private land are generally not available.

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[1] Energy Resource and Development Administration. First Annual Report, Geothermal Energy Research, Development and Demonstration Program. ERDA 77-9, April 1977. p. 81.

TABLE 8-12. STATUS OF GEOTHERMAL LEASES AS OF OCTOBER 31, 1976

State[a]	Producing[b]		Nonproducing		Total Acreage Under Supervision to Date	
	No.	Acreage	No.	Acreage	No.	Acreage
FEDERAL LAND						
Arizona	7	9,594	4	6,508	4	6,508
California			25	34,297	32	43,891
Colorado			38	42,818	38	42,818
Idaho			78	128,906	78	128,906
Montana			5	9,407	5	9,407
Nevada			375	634,683	375	634,683
New Mexico			65	139,203	65	139,203
Oregon			62	94,735	61	94,735
Utah	1	2,463	203	329,678	204	332,141
Wyoming			2	2,804	2	2,804
TOTAL FEDERAL	8	12,057	856	1,423,039	964	1,435,096
INDIAN LAND						
California			2	600	2	600
Nevada (Prosp. Permit)			2	291,590	2	291,590
TOTAL INDIAN			4	292,190	4	292,190

Source: U.S. Geological Survey, Conservation Division. Monthly Geothermal Report October 1976.

[a] North Dakota and South Dakota have no geothermal leases.
[b] None of these areas is commercially productive.

8.4 EXPLORATION

In the past, geothermal areas have been located by obvious surface manifestations such as hot springs, fumaroles, mud pots, and geysers. There have also been accidental discoveries while exploring or drilling for other mineral resources.[1] More scientific techniques are required for estimating the location, depth, volume, temperature, and permeability of heat reservoir rocks. In the exploration of hydrothermal resources, the quantity and chemical composition of geothermal fluids must also be determined.

Exploration techniques in the western United States have developed from disciplines such as geology, geochemistry, geophysics, and hydrology. These exploration techniques vary according to the area investigated and the investigator's preferences.[2]

8.4.1 Technologies

Exploration usually begins with a compilation of available data from published literature and proprietary sources. This initial phase usually entails the study of a large region, perhaps as much as several thousand square kilometers. Reconnaissance fieldwork follows to obtain geologic and geochemical data for several closely related prospects tentatively selected in the first phase. The more promising of these prospects are further investigated in the third phase. In this phase, more intensive fieldwork is undertaken to better define geophysical, geologic, and possibly geochemical properties of the geothermal resource. The fourth and final phase involves the drilling of deep exploration wells.[1]

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 26.

[2] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976. p. 18.

The above sequence for the exploration of geothermal resources requires the following techniques: geologic and hydrologic surveys, geochemical surveys, geophysical surveys, and drilling. These techniques are discussed successively in the following sections.

8.4.1.1 Geologic and Hydrologic Surveys

Geologic and hydrologic surveys are performed to "search for evidence of tectonic activity and seismic disturbance, determine the age and distribution of young volcanic rocks, and locate any surface discharges of steam, water, or warm mud."[2] Data on the temperature and discharge of springs and wells are collected early in the exploration effort. The extent and flow of groundwater are also determined. Aerial photography using visible light, infrared light, and microwave photographic techniques can be useful in locating geological faults and unusually warm ground. These techniques are used for geologic and topographic mapping and structural analysis. Core samples recovered from shallow exploration wells are used to refine the structural model developed from surface data.[1] The objective of these studies is to determine those areas suitable for more detailed investigation.

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976. p. 18.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 29.

8.4.1.2 Geochemical Surveys

Geochemical reconnaissance involves the sampling and analysis of waters and gases from surface manifestations such as hot and cold springs and fumaroles. Chloride analyses can be used to discriminate between liquid- and vapor-dominated hydrothermal resources. Concentrations of silica and ratios of sodium:potassium:calcium can be used to estimate the minimum reservoir temperature of liquid-dominated hydrothermal systems. Variations in the chemistry of nearby waters can be used to evaluate reservoir dimensions and composition.[2] Rock age is determined from solids contained in the water samples.

Geochemical analyses are also performed on core samples recovered from exploration wells. A temperature profile can be estimated from ratios of chemical constituents dissolved in geothermal liquids. Water flow patterns may also be defined from these chemical analyses. This kind of information can help to select more promising drilling sites. Geochemistry can also be used to detect changes in the reservoir during production, testing, and utilization of the geothermal resource.

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976. p. 19.

[2] *Ibid.*, p. 20.

Information obtained from geochemical surveys can be used throughout the life of a geothermal field. Geochemical data can help to determine the ultimate use of the geothermal resource and to design the specific processes to be employed at a particular site. For instance, large quantities of dissolved solids that would precipitate and obstruct flow during expansion or temperature decreases might preclude use of certain types of total flow expanders. Corrosive properties must also be determined before major pieces of equipment are specified. Geochemical data thus provide a basis for specifying the end use of a geothermal resource.[1]

8.4.1.3 Geophysical Surveys

Geophysical surveys are conducted to define specific target areas for drilling. Electrical and electromagnetic surveys of deep resistivity can help to define a hydrothermal reservoir, since hot mineralized fluids are electrically very conductive. Most exploration programs use direct-current surveys, electromagnetic soundings, and sometimes magnetotelluric soundings of deep resistivity (to depths of eight kilometers). These techniques are slow and costly, and are performed only during detailed investigations of particular geothermal targets.[2]

Passive seismic methods are often used to locate geothermal reservoirs. These surveys record and locate microearthquakes and seismic noise, which may be unusually frequent and intense in geothermal reservoirs. Passive seismic surveys are used early in the exploration sequence. Active seismic methods are seldom employed.[1]

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975.

[2] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 19.

If a prospect remains attractive after the initial phases of exploration, shallow exploration wells (200-500 feet in depth) are drilled to measure the temperature gradient. This is the most direct means of obtaining subsurface temperatures. Deep reservoir conditions are estimated by projecting these gradients to greater depth.[2]

Aeromagnetic and ground magnetic surveys, as well as gravity surveys, can be useful in defining the subsurface geologic structure. Such data are usually collected in the early stages of exploration.[3]

8.4.1.4 Drilling

The drilling of shallow exploration wells is requisite in any detailed exploration program. A portable, truck-mounted rotary drill rig is generally used for this kind of hole. Holes 200 to 300 feet deep are required to obtain measurements undisturbed by circulation of shallow groundwater.[4]

The final phase of geothermal exploration is the drilling of deep exploratory wells. Only deep exploratory drilling can determine the true nature of a geothermal prospect in terms of thermal and chemical character and producible energy. Vital data to be obtained are temperature and pressure variations with depth, lithology and stratigraphy, fluid composition (in hydrothermal or geopressured systems), and rock permeability and porosity. These data, together with a full set of geophysical well-logs and well tests, permit complete evaluation of the geothermal prospect.[1]

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 19.

[2] *Ibid.*

[3] *Ibid.*

[4] *Ibid.*, p. 21.

Geothermal wells for deep exploration are generally drilled with rotary rigs common to the petroleum and natural gas industries. The depths required for drilling vary with the geothermal resource. Large volumes of low-enthalpy water suitable for many direct uses may be found in shallow aquifers at depths of less than 1000 feet. High-enthalpy hydrothermal resources are generally found at depths in excess of 2000 feet; many reservoirs extend deeper than 10,000 feet.[2]

In rotary drilling, a drilling fluid must be circulated down through the drill stem to flush out drill cuttings and protect the hole against collapse. This fluid is usually a dense mud containing bentonite clay; at temperatures above 150°C, other compounds must be added to prevent gelling of the mud. Air has been used as the drilling fluid at The Geysers for the high temperature region in the vicinity of the reservoir.[3] A "mud pit" is required for storage of the drill mud and waste fluids flushed up during drilling. Once the drilling reaches the geothermal reservoir, tests are conducted to determine the characteristics of the geothermal resource.[1]

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 20.

[2] *Ibid.*, p. 21.

[3] *Ibid.*, p. 22.

8.4.2 Input Requirements

Inputs required for exploration of a geothermal resource include manpower, materials and equipment, finances, water, land, and ancillary energy. Each of these requirements is successively discussed below. Exploration efforts of the past have emphasized the definition of hydrothermal convection systems. While exploration of igneous and conduction-dominated systems has commenced, little data on the exploration inputs for these systems have been reported. Consequently, the following inputs describe the exploration of hydrothermal convection systems. Exploration inputs for igneous and conduction-dominated systems can be assumed to be on the same order of magnitude.

The input requirements and outputs reported below principally describe an exploration effort designed to locate a hot water geothermal field with a capacity for the production of 100 MW_e electric power for 60-70 years. It is estimated that sixty-four prospects will be evaluated with geologic and geophysical techniques. Half of these will require additional geophysical field work to select twenty-four that justify temperature-hole programs. From that work sixteen prospects will be selected for deep exploratory drilling. It is assumed that one of the sixteen exploratory wells will discover the objective field.

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 20.

Additional testing with the drilling of three confirmation wells will complete the exploration effort.[1,2]

8.4.2.1 Manpower

Manpower requirements for the exploration and appraisal of a 200 MW_e hot water field with a production life of 35 years were prepared by Bechtel Corporation for the Federal Energy Administration. Bechtel's estimates assume an exploration program essentially similar to the one described above. However, Bechtel's manpower projections assume the drilling of thirty-two deep wells; the exploration program defined above assumes the drilling of sixteen exploratory and three confirmation wells. Bechtel's manpower projections are scaled to the drilling efforts assumed in this analysis. These manpower estimates are summarized in Table 8-13. The data assume that sixty calendar days are required to drill each deep well. Two drilling rigs are required for eighteen months.[3,4]

8.4.2.2 Materials and Equipment

The materials and equipment required for geologic, geothermal, and geophysical techniques are standard, and include such

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[1] B. Grieder. "Status of Economics and Financing of Geothermal Energy Power Production." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 2305-2314.

[2] Greider has described the exploration effort to discover a 200 MW_e field; a field of 100 MW_e will require the same effort if the intended development life of the 100 MW_e field is twice that of the 200 MW_e field.

[3] B. Grieder, *op.cit.*

[4] Federal Energy Administration. Interagency Task Force on Geothermal Energy. Project Independence Blueprint Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974, pp. D-3, D-4.

TABLE 8-13. MANPOWER REQUIREMENTS FOR EXPLORATION AND APPRAISAL OF A HOT WATER FIELD WITH A CAPACITY FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER

Skill	Man-years	
	First Year	Second Year
Geologist	3	3
Geophysicist	2	2
Landman	2	1
Drill rig foreman	1	2
Drillers	3	6
Laborers	2	4
Truck drivers	1	2
Geochemists	1	1
TOTAL	15	21

Sources: Federal Energy Administration. Interagency Task Force on Geothermal Energy. Project Independence Blueprint Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974. pp. D-3, D-4.

B. Greider. "Status of Economics and Financing of Geothermal Energy Power Production." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office. 1976. pp. 2305-2314.

items as office space and supplies, maps, access to a properly stocked library and well log file, drafting and mapmaking facilities, and materials for report writing. For the fieldwork and drilling segments of the exploration program, field vehicles and equipment are also required.

In most cases, materials and equipment for drilling will not be provided by those conducting the exploration, but will be provided by a contractor who is commissioned for the drilling. This equipment includes such items as a drill rig, water truck and/or air compressor, mud pumps and handling equipment, drill pipe and bits, and core barrel (if applicable). Facilities and equipment must also be provided for the well-site geochemist, including a logging trailer, and samples description and collection material. Borehole geophysical equipment, including a logging truck and appropriate sondes (probes) are usually provided by a contractor specializing in well logging.

8.4.2.3 Economics

Greider[1] has estimated the cost of an exploration program proving a liquid-dominated system with a capacity for the production of 200 MW_e electric power. Greider's cost estimate is presented in Table 8-14. The cost of exploration will vary with location, geothermal field characteristics, and type of planned development. The costs in Table 8-14 also describe a 100 MW_e field with a production life twice that of the 200 MW_e field.

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[1] Greider, B. "Status of Economics and Financing of Geothermal Energy Power Production." Proceedings Second United Nations' Symposium on the Development and Use of Geothermal Resources, San Francisco, CA, May 20-29, 1975. Washington, D.C.: Government Printing Office, 1976, pp. 2305-2314.

TABLE 8-14. EXPLORATION COSTS TO PROVE A HOT WATER FIELD CAPABLE OF THE PRODUCTION OF 200 MWe ELECTRIC POWER

Activity	Cost[a]
Initial geology and geophysics[b]	$ 2,560,000
Additional geophysics[c]	480,000
Temperature hole programs[d]	960,000
Land acquisition[e]	1,680,000
Deep drilling[f]	
12 Failures	4,380,000
3 Failures with casing run	1,350,000
1 Discovery plus 3 confirmation	1,505,000
Well testing[g]	540,000
TOTAL	$13,455,000

[a] Cost in 1975 dollars.

[b] Based on investigation of 64 areas.

[c] Based on investigation of 32 areas.

[d] Based on investigation of 24 areas.

[e] Assumes acquisition of 7500 acres for each of 32 areas at a cost of $7.00/acre.

[f] Drilling to a depth of 5000 feet.

[g] These tests are used to establish the commercial potential of the geothermal resource.

Source: Greider, B. "Status of Economics and Financing of Geothermal Energy Power Production." Proceedings Second United Stations' Symposium on the Development and Use of Geothermal Resources. San Francisco, CA. May 20-29, 1975. Washington: Government Printing Office. 1976. pp. 2305-2314.

Another estimate of the cost of exploration is reported in Table 8-15. Barr's[1] estimate describes an exploration program to discover one dry steam field. Barr's analysis assumes an initial evaluation on only thirty geothermal prospects, with the drilling of only four deep wells.

8.4.2.4 Water

Water requirements for the application of geologic, geochemical, and geophysical techniques are very small. Water requirements during drilling amount to 200-500 barrels per rig-day, primarily for use as drilling fluid. Using the average consumption of 375 barrels per rig-day[2] and assuming that sixty days are required to drill each well, the average water requirement is calculated to be 22,500 barrels per well. Water requirements for the drilling of 19 wells thus amount to about 55 acre-feet.

8.4.2.5 Land

During the initial stages of exploration, small land areas are disturbed by surface surveying. Somewhat greater disturbances occur during geochemical and geophysical surveys. Even the drilling of shallow temperature gradient wells is confined and

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[1] Barr, R. C. "Geothermal Exploration: Strategy and Budgeting." Proceedings Second United Nations' Symposium on the Development and Use of Geothermal Resources. San Francisco, California, May 20-29, 1975. Washington, D.C.: Government Printing Office, 1976, pp. 2269-2271.

[2] Federal Power Commission. National Gas Survey, Volume II. Washington, D.C.: U.S. Government Printing Office, 1973, p. 74.

TABLE 8-15. EXPLORATION COSTS FOR A THREE-YEAR EXPLORATION PROGRAM DEFINING A FIELD SUFFICIENT FOR A 200 MWe POWER GENERATING FACILITY[a]

Function	First Year	Second Year	Third Year	Total
Management expense	$ 175,000	$ 175,000	$ 175,000	$ 525,000
Target selection/evaluation	150,000	--	--	150,000
Land acquisition/rentals	775,000	475,000	125,000	1,375,000
Detailed geophysics	325,000	650,000	--	975,000
Site selection	--	100,000	300,000	400,000
Deep drilling	--	500,000	1,500,000	2,000,000
Contingencies	150,000	200,000	225,000	575,000
TOTAL	$1,575,000	$2,100,000	$2,325,000	$6,000,000

[a] Costs in 1975 Dollars.

Source: Barr, R.C., "Geothermal Exploration: Strategy and Budgeting." Proceedings Second United Nation's Symposium on the Development and Use of Geothermal Resources. San Francisco, California, May 20-29, 1975. Washington: Government Printing Office. 1976. pp. 2269-2271.

short-lived.[1] However, significant disturbances occur during deep exploratory drilling.

A typical well-drilling operation disturbs about one acre of land from clearings, roads, mud pits and the like. Efficient operators may disturb only one-half acre, but one acre is typical. The drilling of 19 wells will thus temporarily disturb about 19 acres of land. Once drilling operations have ended, only a small residual amount of land is committed to the completed well. The disturbed land can then be restored to its natural state. The well-head itself consumes only a small fraction of an acre per well.[2]

8.4.2.6 Ancillary Energy

Small quantities of fuel for field vehicles are required during fieldwork. Larger quantities of fuel are used for operating drill rigs during the drilling program.

Fuel requirements for drilling vary with rig size, type of rock formation drilled, and well depth. The Federal Power Commission has indicated that 900-1800 gallons of diesel fuel are consumed per rig-day.[3] Assuming a fuel consumption of 1500 gallons per rig-day and a drilling time of sixty days, it is estimated that 90,000 gallons of diesel fuel are required for drilling one well. The drilling of nineteen wells consumes about 1,700,000 gallons of diesel fuel.

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office. June 1976.

[2] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976.

[3] Federal Power Commission. National Gas Survey, Volume II. Washington, D.C.: U.S. Government Printing Office, 1973, p. 74.

8.4.3 Outputs

Outputs produced during the exploration of geothermal resources are discussed in the following sections. These outputs include air emissions, water effluents, solid wastes, noise pollution, occupational health and safety hazards, and odor.

8.4.3.1 Air Emissions

Some air pollutants are generated by field vehicles during exploration, but the quantities are small. Sources of air emissions during drilling include: exhaust from diesel generators; dust and exhaust from vehicles traveling on access roads; and exhaust of gases contained in the geothermal fluids and uncontrolled blowouts. The most important of these emission sources are discussed below.

During exploratory drilling, potentially the largest source of air pollutants is exhaust from diesel generators. Emissions from this source are summarized in Table 8-16. These estimates are based on the diesel fuel requirement and emission factors published by the Environmental Protection Agency.[1] Carbon dioxide emissions are estimated from the carbon content of diesel fuel.

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[1] U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors. Second Edition, Third Printing with Supplements 1-5. Research Triangle Park, North Carolina: February 1976, pp. 3.3.1-1, 3.3.3-2.

TABLE 8-16. AIR EMISSIONS DURING EXPLORATORY DRILLING[a]

Source	Constituent	Quantity
Diesel Generators[b]	Carbon monoxide	87 tons
	Hydrocarbons	32 tons
	Nitrogen oxides	401 tons
	Aldehydes	6 tons
	Sulfur oxides	27 tons
	Particulates	29 tons
	Carbon dioxide	18,400 tons
Geothermal Fluids[c]	Steam	355,000 tons
	Carbon dioxide	2,800 tons
	Ammonia	250 tons
	Methane	180 tons
	Hydrogen sulfide	180 tons
	Nitrogen and argon	110 tons
	Hydrogen	35 tons

[a] The shown values are total emissions during exploratory drilling. The emissions occur evenly over eighteen months.

[b] Based on diesel fuel requirement and EPA emission factors.

[c] Based on emissions at The Geysers.

Source: U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors. Second Edition, Third Printing with Supplements 1-5. Research Triangle Park, North Carolina. February 1976. pp. 3.3.1-1, 3.3.3-2.

Teknekron, Inc. "Fuel Cycles for Electric Power Generation." Comprehensive Standards: The Power Generation Case. EPA No. 68-01-0561. Washington, D.C.: U.S. Environmental Protection Agency, 1975.

Exploratory wells intercepting geothermal fluids are potential emission sources of gaseous substances dissolved in a liquid resource or contained in steam. This emission source is discussed extensively in Section 8.5.3.1. For this analysis, only the discovery and confirmation wells are assumed to be sources of these gaseous contaminants. Total emissions from these four wells are shown in Table 8-16, as extrapolated from data in Table 8-29.[1] The emissions are based on operations at The Geysers. The Geysers are generally considered to have "cleaner" steam than most other geothermal resources. For comparable levels of power production capacity, emissions from many hot water systems are likely to be comparable to or greater than the emissions at The Geysers.[2]

Uncontrolled blowouts occur infrequently, but can be a significant source of air pollution. This source is discussed in Section 8.5.3.1.

8.4.3.2 Water Effluents

Drilling mud and geothermal fluids are the major liquid effluents from well drilling. Muds used in well drilling may contain certain toxic additives. The muds are also usually very basic (pH up to 10) from the addition of sodium hydroxide.[3] A typical drilling mud is 95% water.[4] Based on the water requirement for drilling (see Section 8.4.2.4), approximately 58 acre-feet of mud are used in the drilling of 19 wells. During drilling at The Geysers, sumps with impervious linings or steel tanks are used to contain this liquid effluent and thus prevent the contamination of surface waters. Ground-water supplies are protected from contamination only when the well is cased.[1] After drilling, the water is evaporated from the sump which can then be landfilled.

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[1] Teknekron, Inc. "Fuel Cycles for Electric Power Generation." Comprehensive Standards: The Power Generation Case. EPA No. 68-01-0561. Washington, D.C.: U.S. Environmental Protection Agency, 1975.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977.

[3] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office. June 1976. p. 146.

[4] Campbell, M. D. and J. H. Lehr. Water Well Technology. New York: McGraw-Hill Book Company, 1974, p. 585.

Geothermal fluids are brought to the surface during drilling and well testing. Jones and Stokes Associates have reported that as much as 34,100 cubic meters (approximately 28 acre-feet) of liquid from a liquid-dominated geothermal field may be discharged at the surface from each producing well. In this analysis, only the discovery and confirmation wells are assumed to discharge geothermal fluids. The maximum quantity of geothermal fluids assumed to discharged from these four wells is 112 acre-feet during the eighteen-month exploration program. The fluid may be stored on site in the mud sumps or discharged into the surface drainage system if a National Pollutant Discharge Elimination System (NPDES) permit has been obtained (see Chapter 2 for details).[2] Some sample characterizations of these geothermal fluids have been reported in Section 8.3.4.

Additional contamination of surface and subsurface waters may occur from well blowouts. These infrequent events are discussed in Section 8.5.3.2.

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, pp. 54-56.

[2] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office. June 1976. p. 155.

8.4.3.3 Solid Wastes

The only solid wastes generated during exploration are drill cuttings. Between 0.8 and 1.6 cubic meters of drill cuttings are left on site from each shallow temperature gradient well.[1] For each 5000-foot exploratory well, the volume of drill cuttings amounts to about 0.1 acre-feet. Nineteen deep exploratory wells produce about two acre-feet of drill cuttings. These wastes are typically disposed in mud sumps. After water has evaporated, the sumps are land-filled.

8.4.3.4 Noise Pollution

Noise sources during exploration include: field vehicles, diesel generators, air compressors, and vented gases. The highest noise levels are associated with deep exploratory drilling. Noise levels during drilling are shown in Table 8-17.

8.4.3.5 Occupational Health and Safety Hazards

During fieldwork, personnel are exposed to some very minor hazards such as falls or heat prostration. Drilling operations pose greater but nevertheless minor hazards to crew personnel. Worker exposure to toxic gases is also a hazard and is discussed in Section 8.5.3.5.

8.4.3.6 Odor

Odors during exploration are chiefly associated with the presence of ammonia and hydrogen sulfide. These odors originate

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office. June 1976. p. 155.

TABLE 8-17. NOISE LEVELS DURING THE EXPLORATORY DRILLING OF GEOTHERMAL RESOURCES

Operation	Duration	Noise Level dB(A)	Distance Ft.
Mud drilling	60 days/well	75-80	50
Air drilling, including	30 days/well		
blow line		120	25
blow line with air sampler		95	25
blow line with air sampler and water injection		85	25
Well cleaning, open well	3-6 days	118	50
Well testing, open well	14 days	118	50
Rock muffler		89	50

Source: Ecoview Environmental Consultants. Draft Environmental Impact Report for Geothermal Development of Union Oil Company's Leaseholds on the Upper Part of the Squaw Creek Drainage at the Geysers, Sonoma County, California Napa, California, 1974.

Reed, M. J. and G. E. Campbell, "Environmental Impact of Development in the Geysers Geothermal Field, U.S.A.", Proceedings of the Second United Nations Conference on the Development and Use of Geothermal Resources, San Francisco, CA, May 20-29, 1975. Washington Government Printing Office, 1976.

mainly from geothermal fluids brought to the surface in drilling mud and during well testing. Hydrogen sulfide has a choking odor similar to that of rotten eggs. Its presence can be detected in concentrations as low as .025 ppm.[1] Ammonia has a characteristic pungent odor. Holding effluents in enclosed tanks will help to control odors but no totally effective control is available. Other odorous air pollutants encountered during drilling are sulfur dioxide and nitrogen dioxide, which are emitted principally from diesel equipment.

The inputs and outputs of geothermal exploration are summarized in Table 8-18.

8.4.4 Exploration Social Controls

Exploration and development of geothermal resources is controlled by the owner of the resource, but there is still debate about whether geothermal energy constitutes a water resource (owned by the surface land owner) or a mineral resource (such as oil or gas and owned by the holder of mineral rights).[2] In addition, geothermal energy in hot dry rock is neither an extractable mineral or a fluid, and hence may be subject to different laws altogether.

Therefore, prior to any discussion of jurisdiction over the exploration and development of the geothermal resource, resource ownership must be established. This problem of resource

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[1] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973.

[2] This debate may still exist concerning state or privately owned geothermal resources, but the 9th Circuit Court has held that geothermal energy constituted a mineral resource in its review of U.S. v. Union Oil Co. 549 F.2d 1271 (1977).

TABLE 8-18. SUMMARY OF INPUTS AND OUTPUTS OF AN EXPLORATION EFFORT INTENDED TO DISCOVER A FIELD SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER

Input Requirements	
Manpower	
• first year	15 man-years
• second year	21 man-years
Materials and equipment	Not quantified
Economics	$13 million[a]
Water	55 acre-feet
Land	
• temporary	19 acres
• permanent	less than 1 acre
Ancillary energy	1,700,000 gal. diesel fuel
Outputs	
Air emissions[b]	
• steam	355,000 tons
• carbon dioxide	21,000 tons
• carbon monoxide	87 tons
• hydrocarbons	210 tons
• nitrogen oxides	400 tons
• aldehydes	6 tons
• sulfur oxides	27 tons
• particulates	greater than 29 tons
• ammonia	250 tons
• hydrogen sulfide	180 tons
• nitrogen and argon	110 tons
• hydrogen	35 tons

[a] 1975 dollars.

[b] Over 18 months.

(Continued)

TABLE 8-18. SUMMARY OF INPUTS AND OUTPUTS OF AN EXPLORATION EFFORT INTENDED TO DISCOVER A FIELD SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER (Continued)

Water effluents	
· drilling mud	58 acre-feet
· geothermal fluids	112 acre-feet
Solid wastes	
· drill cuttings	2 acre-feet
Noise pollution	
· well cleaning	118 db(A)[c]
Occupational health and safety	data unavailable
Odors	H_2S NH_3

[c] 50 ft. distance.

ownership as applied to resource regulation will occur repeatedly throughout this chapter.

Table 8-19 illustrates both the difficulty in classifying geothermal energy and the widely ranging solutions used by the states. Note that the western states are mainly found in the group not classifying the geothermal resources.

The Union Oil decision is consistent with that of another court in Geothermal Kinetics vs. Union Oil. The court noted that the water in geothermal resource development is valuable not for water in its normal context, but rather only as a conduit for the energy it gains when in contact with the molten minerals and gases within the resource. The court therefore held that the geothermal resource was owned by the mineral owner.[1]

An additional problem concerning ownership of geothermal resources is its connection to water laws. This is of most importance on federal lands where, by an executive withdrawal of hot springs type waters from public lands in 1930, the Department of Interior suggests that state laws do not apply to those reserved waters.[2]

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[1] Geothermal Kinetics, Inc. v. Union Oil Company, No. 75314 (Super. Ct., Sonoma County, CA, Filed June 1, 1976). Another case is presently in a different California court testing whether a reservation of "all minerals" by the State of California included geothermal resources. See Pariani et al v. State of California, No. 657-291 (Super. Ct., San Francisco County).

[2] Kitchen, Gerald J. "Geothermal Leasing Practices." Geothermal Resources Development Institute. Boulder, Colorado: Rocky Mountain Mineral Law Foundation, 1977, p. 3-14.

TABLE 8-19. CLASSIFICATION OF GEOTHERMAL RESOURCES

Those Not Classifying Geothermal[a]	Classifying It Mineral	Classifying It Water	Not Classified as Mineral or Water
Federal	Hawaii	Wyoming	Idaho
Colorado[b]		Nevada[b]	Montana
Arizona			Washington
Alaska			
New Mexico			
Louisiana			
California			
Texas			
Nevada[c]			
Utah			

[a] South Dakota and North Dakota have no geothermal legislation.

[b] Colorado calls geothermal "not a mineral."

[c] Nevada at first classified geothermal as water, but recently has adopted a non-classification with regulations soon to be promulgated.

Source: Sacarto, Douglas M. State Policies for Geothermal Development. Denver: National Council of State Legislatures, November 1976, p. 44.

8.4.4.1 Exploration Permits on Federal Lands

The Geothermal Steam Act of 1970[1] contains no provisions with respect to granting of exploration rights. However, in accordance with his rule-making authority, the Secretary of Interior has established procedures for undertaking exploratory activities.[2]

Any person desiring to explore for geothermal resources on federal lands must obtain an exploration permit from BLM, whether the exploration is prior to or after the issuance of a lease. Application, entitled "Notice of Intent and Permit to Conduct Exploration Operations (Geothermal Resources)" is made to the district BLM office. This "Notice of Intent" must describe the lands to be explored by township, briefly describe the proposed plan of operation, and estimate the dates of commencement and termination of exploration activities. Simultaneously with the filing, and before the developer enters the land, a bond of not less than $5,000 must be submitted to BLM.[3] The USGS must give administrative approval to the plan for exploration. The explorer may not drill deeper than 500 feet, and the BLM also has broad discretionary authority to establish terms and conditions under which exploration may take place, particularly whether additional measures will be taken to insure that any damaged land will be rehabilitated. BLM may suspend or terminate exploration operations at any time the agency determines there is non-compliance with the terms and conditions of the "Notice of Intent."

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[1] 30 U.S.C. §§1001-1025 (1970).

[2] 43 C.F.R. §3209.

[3] 43 C.F.R. §3209.4-1.

Geothermal exploration permits granted prior to a lease do not give the holder an exclusive right to prospect for resources on the land described in the "Notice of Intent" or any preference rights to geothermal resources or any lease.[1] Upon completion of the exploration, the developer must file with BLM a "Notice of Completion of Exploration Operations." Within 90 days thereafter, the agency notifies the person or corporation who had conducted the exploration whether the terms of the permit have been sufficiently met or whether additional measures need to be taken to rectify any damage to the land. Core drilling or development wells are not allowed under this permit but require that a lease be obtained first.

8.4.4.2 Exploration Permits on State Lands

Six of the eight western states, Wyoming, Arizona, New Mexico, Utah, Montana, and Colorado have adopted geothermal laws. In some cases prospecting permits, though not provided for in state law, may be issued within the discretion of the state leasing agency. Wyoming alone requires a permit by statute.

The term for Wyoming's prospecting permit is three years and may be renewed for two years. Wyoming issues prospecting permits on newly offered land by public drawing, whereas lands previously opened are available for prospecting permits upon application. The permit holder is given the right to convert his permit into lease if the land is reclassified as a Known Geothermal Resource Area (KGRA).

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[1] 43 C.F.R. §3209.0-2.

The remaining five[1] states in the West allow exploration of Non-KGRA lands by issuance of lease. For areas already classified as having geothermal potential, exploration is only permitted on leased land by lease holders. Colorado has provided little statutory authority and gives its state land commissioners the power to specify the leasing provisions. Table 8-20 summarizes the state provisions for exploration of state lands.

TABLE 8-20. EXPLORATION OF STATE LANDS FOR GEOTHERMAL RESOURCES FOR NON-KGRA LANDS[a]

	Newly Offered	Application Overlap[b]
Arizona	By application	Qualifications or Cash Bonus Bidding
Colorado	Determined by Agency	Determined by Agency
Montana	Competitive	Competitive
New Mexico	Competitive	By application
Utah	By application[c]	By application
Wyoming	Public drawing	

[a] South Dakota and North Dakota have no provisions for exploration.

[b] In cases where there is an overlap of applied for lease areas, the administering agency will give priority to applicant by the method listed.

[c] Utah offers newly opened lands for cash bonus bidding only.

Source: Sacarto, Douglas M. State Policies for Geothermal Development. Denver: National Council of State Legislatures, November 1976, p. 48.

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[1] Since North Dakota and South Dakota have limited geothermal potential and have no laws, the five states are Arizona, Montana, Colorado, Utah, and New Mexico.

8.5 EXTRACTION: DRILLING

As shown in Figure 8-1, the extraction of geothermal energy comprises two phases: drilling and production. This section describes only the drilling operation. Facilities required to control and transport the geothermal fluid to its point of utilization are discussed in Section 8.6, Extraction: Production.

8.5.1 Technologies

Geothermal production wells are usually drilled with rotary rigs common to the petroleum and natural gas industries. Several novel drilling methods are being researched to increase the drilling rate, reduce costs, and increase the ultimate depth attainable. Both the rotary and novel drilling methods employ one or a combination of four mechanisms for excavating rock. These include mechanically induced stresses, thermally induced stresses, fusion and vaporization, and chemical reactions.[1]

Mechanically induced stresses are produced by standard rotary drills, explosive drills, and ultrasonic drills. These drills induce mechanical stresses by impact, abrasion, or erosion. Brittle fracturing occurs when these stresses exceed the tensile or shear strength of the rock.[2]

Thermally induced stresses are produced by forced-flame drills, microwave drills, induction drills, and others. These drills generate thermal stresses that fracture rock by inducing thermal expansion.[1]

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[1] Maurer, W. C. Novel Drilling Techniques. Elmsford, New York: Pergamon Press, 1969.

[2] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 30.

Rocks may be fused or vaporized by introducing heat at a rate sufficient to produce local temperatures greater than the melting or vaporization temperatures of the rock. This principle is employed by electric heater drills, electron beam drills, and laser drills.[2]

Chemical drills use highly reactive chemicals to dissolve rock. Chemicals may also be used to alter rock hardness in order to increase the drilling rate of standard drills.[3]

In standard rotary drilling, a drilling fluid is circulated to cool the drill bit and remove rock cuttings from the bore hole. The drilling fluid is usually a dense mud containing bentonite clay and water; at temperatures above 150°C, additives are required to prevent gelling of the mud.[4] Drilling mud deteriorates rapidly at temperatures above 177°C, slowing the circulation of cuttings being removed. High-temperature drilling fluids are still under development.[5] A cooling tower may be required to cool drilling mud.

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 30.

[2] *Ibid.*

[3] *Ibid.*

[4] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 22.

[5] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 31.

Air is also used as drilling fluid.[1] Advantages of air drilling are:

- higher drilling speeds and lower drilling costs
- less damage to production zone from clogging by circulating mud
- no requirements for storage of drilling mud.

Air drilling is not suitable for those formations bearing much water or having strong sloughing tendencies. Air drilling may be unable to provide sufficient cooling to the drill bit.[2] Typically, mud drilling is employed when drilling through water-bearing formations. Air drilling may then be used to drill through the deeper formations containing no water. A typical well configuration at The Geysers is shown in Figure 8-6.

Rock formations in geothermal areas are generally fractured and faulted, causing frequent losses of drilling fluid. Thus, drilling will proceed more slowly than the drilling for natural gas or petroleum.[3] The hard abrasive rock surrounding geothermal resources is difficult to penetrate even with tungsten carbide

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 31.

[2] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 22.

[3] *Ibid.*

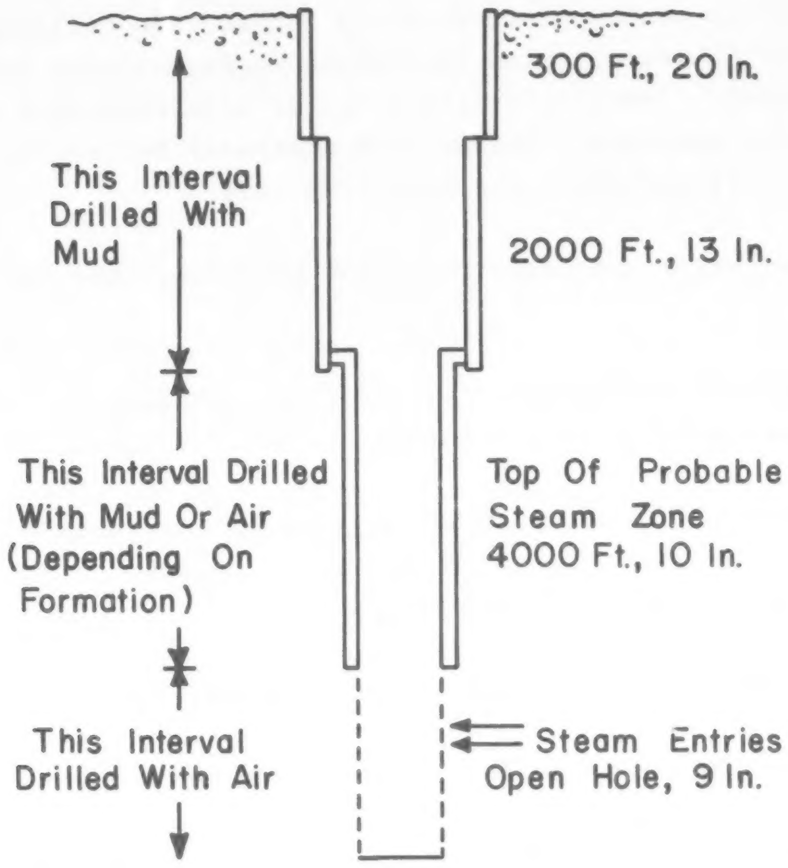
300 Ft., 20 In.
This Interval Drilled With Mud
2000 Ft., 13 In.
This Interval Drilled With Mud Or Air (Depending On Formation)
Top Of Probable Steam Zone 4000 Ft., 10 In.
This Interval Drilled With Air
Steam Entries Open Hole, 9 In.

Figure 8-6. Typical Well Configuration at the Geysers.

Source: Budd, C. F., Jr. "Steam Production at the Geysers Geothermal Field," Geothermal Energy: Resources, Production, Stimulation. P. Kruger and C. Otte, eds. Stanford, California: Stanford University Press, 1973.

bits. The hard rock slows drilling and increases the wear of bits, causing more frequent replacement.[1]

Wells may be drilled directionally, in order to reach a desired subsurface position not directly beneath the drilling site. This may be necessitated by limited surface access for vertical drilling. Vertical drilling is far less expensive and is more commonly employed. The maximum practical horizontal reach of a well is probably less than 5000 feet.[2,3]

Geothermal wells are cased above the producing zone for four reasons:

1) to prevent undesirable fluids of low enthalpy or high acidity from entering the well;

2) to prevent the sloughing or erosion of particles above the production zone that could damage piping, valves, and turbines;

3) to prevent contamination of ground water; and

4) to provide an anchor for a blowout preventer.[4]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 31.

[2] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 22.

[3] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 31.

[4] Jones and Stokes Associates, *op.cit.*, p. 31.

The production zone may be bare (no casing), have a slotted liner, or a solid liner perforated after setting in place. The casing is cemented to the formation to prevent vibration, to insure that geothermal fluids do not erupt in the annulus between the casing and the drill hole, and to prevent the casing from being ejected from the drill hole. Special high-temperature cements and in special cases acid-resistant cements are used and being developed.[1]

The extraction of geothermal fluids from the geopressured zones of the Gulf Coast requires wells drilled to 12,000-15,000 feet. Large volumes of low-enthalpy water suitable for many non-electric uses are found in shallow aquifers at depths of less than 1000 feet. High-enthalpy hydrothermal resources are generally found at depths in excess of 2000 feet; many reservoirs extend deeper than 10,000 feet.[2] Completed wells at The Geysers range from 600 to 9000 feet. To date, no geothermal wells have been drilled beyond 10,000 feet.

The spacing of production wells has been described by Jones and Stokes Associates:[3]

> Wells should be spaced close enough to maximize the rate of production from a given field, or portion of a field, and far enough apart so as not to interfere with each other. Wells are said to interfere when production from one well reduces production from a neighboring well. Optimum spacing is governed by the

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 31.

[2] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, p. 21

[3] *Ibid.*, pp. 25, 28.

> porosity and permeability of the reservoir rocks, and these may be expected to vary widely. At The Geysers, optimum well spacing has been found to be one per 16 hectares (40 acres). In many countries, a spacing of from 90 to 300 meters (300 to 1,000 feet) has been employed. (That spacing is equivalent to one well per two to 22 acres.)

8.5.2 Input Requirements

Input requirements and outputs of geothermal drilling are defined by the required number of production wells. The requried number of wells depends on the characteristics and type of geothermal resource and on the proposed utilization of the geothermal fluid. In this analysis, the geothermal fluid is used to produce 100 MW_e of electric power. Four resource developments are analyzed:

1) a 150°C liquid-dominated resource using a binary-fluid cycle for power production;

2) a 150°C liquid-dominated resource using direct steam flashing for power production;

3) a hot rock development utilizing a pressurized fluid at 250°C with a binary-fluid cycle for power production;

4) a vapor-dominated system similar to The Geysers.

The liquid-dominated resource at Wairakei, New Zealand, uses a direct steam flashing cycle to produce electricity. In

1971, 61 wells supplied a power plant producing 160 MW_e.[1] Based on the facility at Wairakei, 38 production wells are required for a plant producing 100 MW_e. Milora and Tester[2] prepared designs for both flashed steam and binary fluid cycles using a 150°C geothermal fluid. A binary-fluid cycle was estimated to require approximately 4400 lb/sec geothermal fluid, while a flashed steam cycle[3] required a geothermal fluid flow of about 4800 lb/sec. Based on a conservative well flow rate of 100 lb/sec, flashed steam and binary-fluid cycles power plants require 48 and 44 production wells, respectively.[4]

A binary-fluid cycle using a 250°C fluid requires a fluid flow of about 1450 lb/sec.[5] Milora and Tester assumed a well fluid flow of about 300 lb/sec.[6] Thus, approximately five production wells are required for this development scheme for the utilization of energy stored in hot rock.

At The Geysers, 75 wells produce steam sufficient for the generation of 502 MW_e. A 100 MW_e development would require 15-20 wells.[7]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 46.

[2] Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press, 1976.

[3] With a heat rejection temperature of 27°C.

[4] Milora, S. L. and J. W. Tester, *op.cit.*

[5] *Ibid.*, p. 103.

[6] *Ibid.*, p. 93.

[7] Resource Planning Associates, Inc.,*op.cit.*, p. 20.

Reinjection wells may also be required to dispose of "spent" geothermal fluids. At The Geysers, one large reinjection well can dispose of wastewater from each 100 MW_e generating facility.[1] The FEA[2] and Anglin[3] have anticipated one reinjection well for every two production wells of a liquid-dominated geothermal fluid. Milora and Tester[4] assumed a greater requirement for reinjection wells on the basis that formation permeability might limit the reinjection flow rate. In this analysis, Milora and Tester's conservative estimate of equal numbers of production and reinjection wells is assumed.[5]

Production from wells at The Geysers has been observed to diminish with development. Overall production decreases at the rate of 14 percent each year.[6] To maintain production, new wells must be drilled at the rate of 14 percent per year.[7] Over a thirty year period, an additional 60-80 wells are required to maintain production at 100 MW_e. A similar depletion of water-dominated systems has not been observed.[1] Depletion of water-dominated systems is expected to vary from site to site. If all of the spent geothermal fluids are reinjected, the productivity of the resource may be maintained.[2]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 56.

[2] Federal Energy Administration, Interagency Task Force on Geothermal Energy. Project Independence Blueprint, Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974, p. D-3.

[3] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976, p. 28.

[4] Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press, 1976.

[5] *Ibid.*,.p. 92.

[6] Kruger, P. and C. Otte, eds. Geothermal Energy. Stanford, CA.: Stanford University Press, 1973.

[7] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 54.

The above estimated well requirements are summarized in Table 8-21. These requirements assume an additional 20% requirement for reserve capacity.[3,4]

Manpower, materials and equipment, finances, water, land, and ancillary energy requirements for the drilling of geothermal resources are discussed in the following sections.

8.5.2.1 Manpower

Manpower requirements for developmental drilling of hydrothermal convection systems have been prepared by Bechtel Corporation for the Federal Energy Administration.[5] Bechtel's estimates

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 58.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 60.

[3] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976.

[4] The Futures Group, *op.cit.*, p. 54.

[5] Federal Energy Administration, Interagency Task Force on Geothermal Energy. Project Independence Blueprint, Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974, p. D-5.

TABLE 8-21. WELL REQUIREMENTS FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER[a]

Geothermal Resource	Fluid Temperature	Power Production Technology	Required Number of Wells Production	 Reserve	 Reinjection	 Additional
1. Hot Water	150°C	Binary-fluid cycle[b]	44[f]	11[f]	44[h]	--
2. Hot water	150°C	Direct steam flashing cycle[c]	48[f]	12[f]	48[h]	--
3. Hot Rock	250°C	Binary-fluid cycle[d]	5[g]	1[g]	5	--
4. Steam	240°C	Direct use of steam[e]	15-20[e]	4-5[e]	1	60-80[i]

[a] Based on data and assumptions reported in text.

[b] Assumes geothermal fluid requirements of 4400 lb/sec.

[c] Assumes geothermal fluid requirements of 4800 lb/sec.

[d] Assumes geothermal fluid requirements of 1450 lb/sec.

[e] Based on Geysers.

[f] Assumes well flow of 100 lb/sec.

[g] Assumes well flow of 300 lb/sec.

[h] May be half assumed value.

[i] Due to well depletion, new wells must be drilled at 14% per year. Reported value is total requirement over 30-year period.

describe the manpower required to drill 34 wells. Estimates reported herein are simply scaled from those reported by Bechtel. These estimates describe the following activities:

- developing a reservoir model
- siting and drilling all wells
- performing preliminary well tests and well-logging
- casing and cementing all wells through the well-head valves to complete shut-in
- conducting well-flow tests and chemical sampling.

Table 8-22 reports the manpower required to complete the above tasks. The data assume that sixty days are required to drill and complete each well and that the average well depth is 5000 feet.

8.5.2.2 Materials and Equipment

Current estimates of materials and equipment required for geothermal drilling are unavailable. Various equipment is temporarily committed for road construction, drilling pad construction, sump construction, and drilling. Equipment required for construction includes heavy bulldozers, road graders, carry-alls, soil compactors, water trucks, and supporting lubrication and gasoline trucks. Drilling operations require heavy-duty oil well drilling equipment. A tower 90-120 feet high is used to raise sections of pipe successively into position

TABLE 8-22. MANPOWER REQUIREMENTS FOR THE DRILLING OF WELLS SUFFICIENT FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER

	Manpower Requirements, Man-Years							
	Hot Water Resource Binary-Fluid Cycle[a]		Hot Water Resource Direct Steam Flashing Cycle[b]		Hot Rock Resource Binary-Fluid Cycle[c]		Dry Steam Resource Direct Use of Steam[d]	
	(1.0 year)[e] First year	(0.2 year)[e] Second year	(1.0 year)[e] First year	(0.2 year)[e] Second year	(1.0 year)[e] First year	(0.2 year)[e] Second year	(1.0 year)[e] First year	(0.2 year)[e] Second year
Reservoir Modeling								
Reservoir Engineer	2.2	0	2.4	0	0.2	0	0.4-0.6	0
Theoretical Geologist	0.9	0	1.0	0	0.1	0	0.2	0
Geophysicist	0.9	0	1.0	0	0.1	0	0.2	0
Hydrologist	0.9	0	1.0	0	0.1	0	0.2	0
Geochemist	0.9	0	1.0	0	0.1	0	0.2	0
Applied Mathematician	2.2	0	2.4	0	0.2	0	0.4-0.6	0
Mathematical Technician	2.2	0	2.4	0	0.2	0	0.4-0.6	0
Draftsman	0.7	0	0.8	0	~0	0	0.1-0.2	0
Well Drilling								
Geologist (Core-Logger)	5.8	1.2	6.4	1.3	0.6	0.1	1.2-1.5	0.2-0.3
Drilling Superintendent	2.9	0.6	3.2	0.6	0.3	0.1	0.6-0.8	0.1-0.2
Rig Foreman	12.	2.3	13.	2.5	1.3	0.3	2.4-3.1	0.5-0.6
Driller	47.	9.3	51.	10.	5.2	1.0	9.4-12.	1.9-2.4
Pipe-Fitter	12.	2.3	13.	2.5	1.3	0.3	2.4-3.1	0.5-0.6
Welder	5.8	1.2	6.4	1.3	0.6	0.1	1.2-1.5	0.2-0.3
Crane Operator	2.9	0.6	3.2	0.6	0.3	0.1	0.6-0.8	0.1-0.2
Truck Driver	5.8	1.2	6.4	1.3	0.6	0.1	1.2-1.5	0.2-0.3
Laborer	35.	7.0	38.	7.6	3.9	0.8	7.1-9.2	1.4-1.8
Well Testing								
Reservoir Engineer	2.2	0.6	2.4	0.6	0.2	0.1	0.4-0.6	0.1-0.2
Mechanical Engineer	4.4	1.2	4.8	1.3	0.5	0.1	0.9-1.1	0.2-0.3
Geochemist	2.2	0.6	2.4	0.6	0.2	0.1	0.4-0.6	0.1-0.2
Mechanical Technician	4.4	1.2	4.8	1.3	0.5	0.1	0.9-1.1	0.2-0.3
TOTAL	150	29	170	32	17	3.2	31-40	5.7-7.7

[a] Drilling requirement of 99 wells.

[b] Drilling requirement of 100 wells.

[c] Drilling requirement of 11 wells.

[d] Drilling requirement of 20-26 wells; does not include additional 60-80 wells required over 30-year period, assuming depletion rate of 14% per year.

[e] Duration of effort.

Source: Federal Energy Administration, Interagency Task Force on Geothermal Energy. Project Independence Blueprint, Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974. p. B-5.

for drilling. Heavy-duty diesel electric generators, mud pumps, and other drilling accessories are located adjacent to the tower.[1]

Materials permanently committed at a well site are the casing and tubing installed in each well. Based on Figure 8-6, the total weight of steel committed to each well is 185 tons.[2] For a hot water field producing 100 MW_e electric power, steel requirements range from 18,000-20,000 tons. Development of a hot rock field producing 100 MW_e requires only 2000 tons of steel. Steel requirements for a dry steam field producing 100 MW_e amount to 15,000-20,000 tons. These estimates are based on the well requirements of Table 8-21.

8.5.2.3 Economics

The cost of drilling and casing geothermal wells is determined mainly by the type of rock, diameter of the well and its depth. Milora and Tester have developed a geothermal well cost model using cost information for oil and gas wells as a basis for extrapolating the limited available cost data for geothermal wells.[3] This model is reproduced as Figure 8-7.

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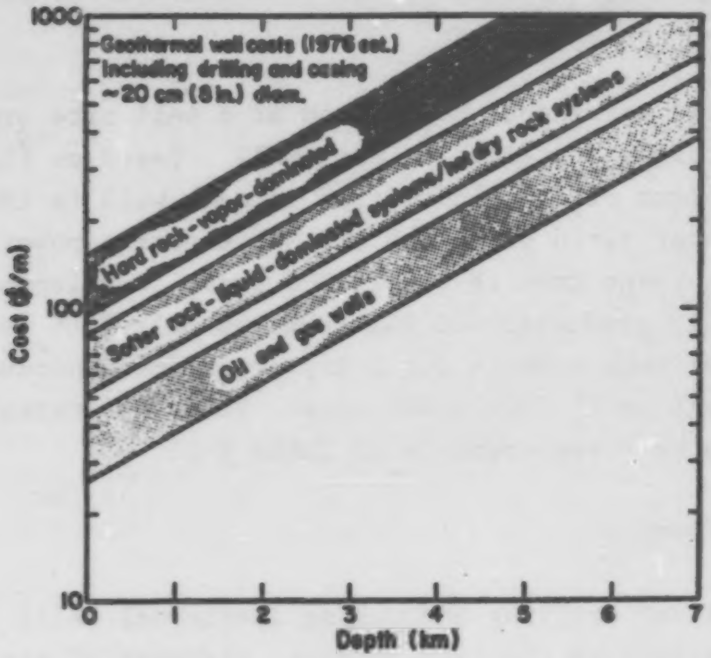
[1] Jones and Stokes Associates. *Geothermal Handbook*. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976, pp. 143-149.

[2] This steel requirement assumes an average casing thickness of 3/8 inch for the first 4000 feet, with a tubing thickness of 1/3 inch for the entire 6000 feet.

[3] Milora, S. L. and J. W. Tester. *Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria*. Cambridge, Massachusetts: The MIT Press, 1976, p. 82.



Note: All cost data in 1976 dollars.

Figure 8-7. Geothermal Well Costs as a Function of Depth.

Reprinted by permission of MIT Press from Stanley L. Milora and Jefferson W. Tester, Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. @ 1976 by the Massachusetts Institute of Technology.

Sources of cost data for Milora and Tester's model are reported below.[1-7]

Glass[8] has reported the cost of a completed steam well at the Geysers to be approximately $1,000,000 in 1977 dollars. Components of this cost are shown in Table 8-23.

Estimated well costs for hot water, hot rock, and dry steam developments are shown in Table 8-24. These costs are based on cost data from Figure 8-7 and Table 8-23 as applied to the well requirements tabulated in Table 8-21.

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[1] Altseimer, J. H. "Geothermal Well Technology and Potential Applications of Subterrene Devices - A Status Review." Los Alamos Scientific Laboratory Report LA-5689-MS, Los Alamos, New Mexico, August 1974.

[2] Greider, R. "Economic Considerations for Geothermal Exploration in the Western United States." Presented at the Symposium of Colorado Department of Natural Resources, Denver, Colorado, December 1973.

[3] *1972 Joint Association Survey of the U.S. Oil and Gas Producing Industry*. Section I, Drilling Costs, and Section II, Expenditures for Exploration, Development and Production, November 1973.

[4] *1973 Joint Association Survey of the U.S. Oil and Gas Producing Industry*. Section I, Drilling Costs, February 1975.

[5] Bee Dagum, E. M. and K. P. Heiss. "An Econometric Study of Small and Intermediate Size Diameter Drilling Costs for the United States." PNE-3012. Mathematica, Princeton, New Jersey. Prepared for U.S. Atomic Energy Commission. June 1968.

[6] Shoemaker, E. M., ed. "Continental Drilling." Report of the Workshop on Continental Drilling, Albiquiu, New Mexico. Washington, D.C.: Carnegie Institution. June 1975.

[7] Hendron, R. Los Alamos Scientific Laboratory, Los Alamos, New Mexico. September 1975.

[8] Glass, W. A. "1977 Drilling Methods and Costs at the Geysers." *Geothermal Resources Council, Transactions*. Vol. 1, May 1977, pp. 103-105.

TABLE 8-23. COMPONENT COSTS OF A COMPLETED STEAM WELL SUNK TO A DEPTH OF 8000 FEET[a]

Item	Cost
Build road, location, & cellar	$ 50,000
Move rig in and out	65,000
Rig operating for 70 days	315,000
Air compressor rental	40,000
Fuel for rig and air compressors	34,000
Excessive drill pipe wear	25,000
Hardbanding drill pipe	3,000
Drill pipe & drill collar inspection	6,000
Water	15,000
Waste disposal	20,000
20" conductor pipe	4,500
13-3/8" casing	52,500
9-5/8" casing	67,500
Cement & services	50,000
Rent 20" Hydril & Rotating Head	10,000
Rent shock sub & stabilizer	10,000
Rent monel drill collar & directional instruments	10,000
Drilling mud	30,000
Well head & muffler & flow line	20,000
Miscellaneous transportation	10,000
Logging	8,000
Mud well logging	25,000
Bits	55,000
Miscellaneous	50,000
Direct supervision & overhead	28,000
TOTAL	$1,003,500

[a] Costs in 1977 dollars.

Source: Glass, W. A. "1977 Drilling Methods and Costs at the Geysers." Geothermal Resources Council, Transactions, Vol. 1, May 1977, pp. 103-105

TABLE 8-24. ESTIMATED WELL COSTS FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER

Resource Development System	Required Number of Wells	Well Depth	Drilling Costs
1. Hot Water			
Binary-fluid cycle	99	8,200 ft	$43,300,000[a]
Direct steam flashing cycle	108	8,200 ft	$47,300,000[a]
2. Hot Rock			
Binary-fluid cycle	11	13,000 ft	$13,000,000[a]
3. Dry Steam	20-26[b]	8,000 ft	$20,000,000-$26,000,000[c]
	80-106[d]	8,000 ft	$80,000,000-$106,000,000[c]

[a] 1976 Dollars.

[b] Initial drilling requirement.

[c] 1977 Dollars.

[d] Drilling requirement over 30-year period, based on depletion of 14% per year.

Sources: Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press, 1976.

Glass, W. A. "1977 Drilling Methods and Costs at the Geysers." Geothermal Resources Council, Transactions, Vol. 1, May 1977, pp. 103-105.

8.5.2.4 Water

Water requirements during drilling amount to 200-500 barrels per rig-day, primarily for use as drilling fluid. Using the average consumption of 375 barrels per rig-day[1] and assuming that sixty days are required to drill each well, the average water requirement is calculated to be 22,500 barrels per well. Water requirements for drilling operations for hot water, hot rock, and dry steam developments are tabulated in Table 8-25.

8.5.2.5 Land

A typical well-drilling operation disturbs about one acre of land. Efficient operators may disturb only one-half acre, but one acre is typical.[2] At the Geysers, wells are spaced at about one well per forty acres. At Ahuachapan, El Salvador, wells are spaced at one per twenty acres, while at Cerro Prieto, Mexico, the wells are spaced at one well per ten acres.[3] Based on these land disturbances and well spacing requirements, total land disturbances and requirements can be estimated. These estimated disturbances and requirements are summarized in Table 8-26.

Once drilling operations have ended, only a small residual amount of land is committed to the completed well. The wellhead itself consumes only a small fraction of an acre per well.

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[1] Federal Power Commission. National Gas Survey, Volume II. Washington, D.C.: U.S. Government Printing Office, 1973, p. 74.

[2] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 4, 1976, p. 26.

[3] *Ibid.*, p. 33.

TABLE 8-25. ESTIMATED WATER REQUIREMENTS FOR DRILLING WELLS SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER

Resource Development System	Required Number of Wells	Estimated Water Requirements[a]
1. Hot Water		
Binary-fluid cycle	99	290 acre-feet
Direct steam flashing cycle	108	310 acre-feet
2. Hot Rock		
Binary-fluid cycle	11	32 acre-feet
3. Dry steam	20-26[b]	58-75 acre-feet
	80-106[c]	230-310 acre-feet

[a] Represents only water required during drilling phase.

[b] Initial drilling requirement.

[c] Drilling requirement over 30-year period, based on depletion of 14% per year.

Source: Federal Power Commission. National Gas Survey, Volume II. Washington, D.C.: U.S. Government Printing Office, 1973. p. 74.

TABLE 8-26. ESTIMATED LAND DISTURBANCE AND REQUIREMENTS FOR DRILLING WELLS SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER

Resource Development System	Land Areas Disturbed By Drilling	Land Areas Required for Assumed Well Spacing
1. Hot Water		
Binary-fluid cycle	99 acres[a]	990-4000 acres[b]
Direct steam flashing cycle	108 acres[a]	1100-4300 acres[b]
2. Hot Rock		
Binary-fluid cycle	11 acres[a]	110-440 acres[b]
3. Dry Steam	20-26 acres[a,c]	800-1000 acres[d]
	80-106 acres[a,e]	3200-4200 acres[d]

[a] Based on one acre disturbed per well.

[b] Based on well spacing of 1 well per 10-40 acres.

[c] Initial requirement.

[d] Based on well spacing of 1 well per 40 acres.

[e] Drilling requirement over 30-year period, based on depletion of 14% per year.

Source: Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976. pp. 26, 33.

There are, however, other land requirements associated with each well-head, such as service roads, pumps, standby generators, and the like.[1] These land requirements are discussed in Section 8.6, Extraction: Production.

8.5.2.6 Ancillary Energy

Fuel requirements for drilling vary with rig size, type of rock formation drilled, well depth, and time on well. The Federal Power Commission has indicated that 900-1800 gallons of diesel fuel are consumed per rig-day.[2] Assuming a fuel consumption of 1500 gallons per rig-day and a drilling time of sixty days, it is estimated that 90,000 gallons of diesel fuel are required for the drilling of one well. Estimated energy requirements for drilling operations for hot water, hot rock, and dry steam developments are tabulated in Table 8-27.

8.5.3 Outputs

Outputs produced from the developmental drilling of geothermal resources are discussed in the following sections. Outputs discussed below include air emissions, water effluents, solid wastes, noise pollution, occupational health and safety hazards, and odor.

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[1] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976, p. 31.

[2] Federal Power Commission. National Gas Survey, Volume II. Washington, D.C.: U.S. Government Printing Office, 1973, p. 74.

TABLE 8-27. ESTIMATED ENERGY REQUIREMENTS FOR DRILLING WELLS SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER

Resource Development System	Required Number of Wells	Diesel Fuel Requirement,[a] 10^6 gal	Energy Equivalent,[b] 10^{12} Btu
1. Hot Water			
Binary-fluid cycle	99	8.9	1.2
Direct steam flashing cycle	108	9.7	1.4
2. Hot Rock			
Binary-fluid cycle	11	0.99	0.14
3. Dry steam	20-26[c] 80-106[d]	1.8-2.3 7.2-9.5	0.25-0.33 1.0-1.3

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[a] Based on fuel consumption of 90,000 gallons diesel fule per well.

[b] Assumes 140,000 Btu/gal.

[c] Initial requirement.

[d] Drilling requirement over 30-year period, based on depletion of 14% per year.

Source: Federal Power Commission. National Gas Survey, Volume II. Washington, D.C.: U.S. Government Printing Office. 1973. p. 74.

8.5.3.1 Air Emissions

Sources of air emissions during drilling include: exhaust from diesel generators; dust and exhaust from vehicles traveling on access roads; and exhaust of gases contained in the geothermal fluids. Uncontrolled blowouts, which have occurred infrequently, also represent a potential source of air pollutants. The most important of these emission sources are discussed below.

Air emissions from diesel generators are summarized in Table 8-28. These data are based on the fuel requirements of Table 8-27 and emission factors published by the Environmental Protection Agency.[1] Carbon dioxide emissions are estimated from the carbon content of the diesel fuel.

In vapor-dominated fields such as The Geysers, dry steam is released to the atmosphere during well drilling, during subsequent well cleanout, and again during production testing. An average well at The Geysers emits about 33 lb/hour of hydrogen sulfide during well testing. Each well is cleaned and tested for approximately twenty days. In that time, over 15,800 lb of hydrogen sulfide are emitted from each well.[2]

Following production testing, the well is discharged continuously through a bleed line until connections are made to a power plant. The average steam and hydrogen sulfide flows

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[1] U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors. Second Edition, Third Printing with Supplements 1-5. Research Triangle Park, North Carolina: February 1976, pp. 3.3.3-1, 3.3.3-2.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, pp. 71-72.

TABLE 8-28. TOTAL AIR EMISSIONS FROM THE OPERATION OF DIESEL GENERATORS DURING DRILLING OF GEOTHERMAL WELLS SUFFICIENT TO PRODUCE 100 MW_e ELECTRIC POWER

Resource Development System	Diesel Fuel Requirement,[a] 10^6 gal	Air Emissions, Tons[b]						
		Carbon Monoxide	Hydrocarbons	Nitrogen Oxides	Aldehydes	Sulfur Oxides	Particulates	Carbon Dioxide[c]
1. Hot Water								
Binary-fluid cycle	8.9	450	170	2100	31	140	150	96,000
Direct steam flashing cycle	9.7	490	180	2300	34	150	160	100,000
2. Hot Rock								
Binary-fluid cycle	0.99	50	19	230	3.5	15	17	11,000
3. Dry Steam	1.8-2.3[d]	92-120	34-43	420-540	6.3-8.1	28-36	30-39	19,000 - 25,000
	7.2-9.5[e]	370-480	130-180	1700-2200	25-33	110-150	120-160	78,000 - 100,000

[a] Based on fuel consumption of 90,000 gallons diesel fuel per well.

[b] Based on EPA emission factors; carbon dioxide emissions estimated from carbon content of diesel fuel.

[c] Calculated by using fuel density of 41.5°API (specific gravity of 0.82), carbon content of fuel of 86%. All carbon was assumed to be combusted to carbon dioxide.

[d] Initial requirement.

[e] Drilling requirement over 30-year period, based on depletion of 14% per year.

Sources: U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors. Second Edition, Third Printing with supplements 1-5. Research Triangle Park, North Carolina. February 1976. pp. 3.3.3-1, 3.3.3-2.

Reid, W. T. *et al.* "Heat Generation and Transport." Chemical Engineers' Handbook Fifth Edition. R. H. Perry and C. H. Chilton, eds. New York: McGraw Hill Book Co. 1973. pp. 9-9, 9-10.

through the bleed line are small, only about 990 lb/hour and 0.22 lb/hr respectively. However, the period of discharge is variable and can be as long as several years.[1]

Total emissions of steam from well drilling, cleanout, and production testing are shown in Table 8-29. These estimates represent total quantities of steam released to the atmosphere prior to power plant operation. Noncondensable gases are currently uncontrolled at The Geysers during well drilling, cleanout, and production testing. Emissions of particulate matter are controlled by the injection of water into the "blow-line" and the use of mufflers.[2]

Uncontrolled blowouts occur infrequently, but can be a significant source of air pollution. One such uncontrolled blowout at The Geysers has emitted 4000 tons of hydrogen sulfide, 5000 tons of methane, and 6000 tons of ammonia between 1957 and 1975. This is equivalent to about one-eighth the total that would have been emitted from a 100 MW_e Geysers facility operating over the same period without special controls.[3]

Estimates of emissions from the development of liquid-dominated systems can be prepared only from a detailed site-specific analysis of the chemistry of the geothermal fluid.[4] Characteristics of geothermal fluids from several U.S. geothermal fields have been previously described in Section 8.3.4. However,

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 72.

[2] *Ibid.*

[3] *Ibid.*

[4] *Ibid.*, p. 74.

TABLE 8-29. TOTAL EMISSIONS OF GEOTHERMAL STEAM DURING DRILLING, CLEAN-OUT, AND PRODUCTION AT THE GEYSERS FOR A WELL CAPACITY OF 100 MW_e IN ELECTRIC POWER[a]

Constituent	Concentration, wt. %	Quantity Emitted, tons
Steam	99.0	1,330,000
Carbon dioxide	0.79	10,600
Ammonia	0.07	940
Methane	0.05	670
Hydrogen sulfide	0.05	670
Nitrogen and argon	0.03	400
Hydrogen	0.01	130

[a] Scaled from data for 1000 MW_e complex.

Sources: Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 72.

Teknekron, Inc. "Fuel Cycles for Electric Power Generation." Comprehensive Standards: The Power Generation Case. EPA No. 68-01-0561. Washington, D.C.: U.S. Environmental Protection Agency, 1975.

Finney, J.P., F.J. Miller, and D.B. Mills. "Geothermal Power Project of Pacific Gas and Electric Company at The Geysers, California." IEEE Trans. Power App. Systems PAS-92 (1973): 108-115.

these resource characterizations are not sufficient to produce reliable estimates of air emissions during geothermal drilling.

During well drilling and production testing, steam flashed from the geothermal hot waters may represent 20-25 percent of the total fluid, depending on the fluid temperature. For comparable levels of electricity generation, the total quantities of gases emitted to the atmosphere during drilling and production testing are probably comparable to emissions from The Geysers. Since hot water wells in some fields can be completely shut off after production testing, well bleeding prior to power plant operation may not be an air pollution source.[1,2]

Mercury and radon-222 are among the more important trace constituents of geothermal fluids. These elements are toxic even at low concentrations. Mercury is washed from the atmosphere by rain and can be absorbed into living organisms from water or through the food chain. Radon is the precursor of highly toxic but short-lived decay products. Typical concentrations of these contaminants have not been reported.[3]

3.5.3.2 Water Effluents

Drilling mud and geothermal fluids are the major liquid effluents from well drilling. Muds used in well drilling may contain certain toxic additives. The muds are also usually

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 74.

[2] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973.

[3] Resource Planning Associates, Inc., *op.cit.*, pp. 68, 71.

very basic (pH up to 10) from the addition of sodium hydroxide.[1] Typically, drilling mud is 95% water.[2] Based on the water requirements for drilling (see Section 8.5.2.4), approximately 23,700 barrels (approximately 3 acre-feet) of mud are used at each well. To prevent the contamination of surface waters, the drill mud must be contained. At The Geysers sumps with impervious linings or steel tanks are used to contain these liquid wastes.[3] The water is eventually evaporated from the mud, which can then be land-filled.

A significant quantity of geothermal fluids is brought to the surface during drilling and well testing. Jones and Stokes Associates have reported that as much as 34,100 cubic meters (approximately 28 acre-feet) of liquid from a liquid-dominated geothermal field may be discharged at the surface. The geothermal fluid may be stored on site in the mud sumps or discharged into the surface drainage system.[4] Some sample characterizations of these geothermal fluids have been reported in Section 8.3.4.

Quantities of liquid effluents from drilling for hot water, hot rock, and steam geothermal developments are summarized in Table 8-30.

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[1] Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-0008-968. U.S. Government Printing Office, June 1976. p. 146.

[2] Campbell, M. D. and J. H. Lehr. Water Well Technology. New York: McGraw-Hill Book Company, 1974, p. 585.

[3] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, pp. 54-56.

[4] Jones and Stokes Associates, *op.cit.*, p. 155.

TABLE 8-30. ESTIMATED QUANTITIES OF WATER EFFLUENTS PRODUCED DURING DRILLING AND TESTING OF WELLS SUFFICIENT FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER

Geothermal Resource	Drilling Mud[a]	Geothermal Liquids[b]
1. Hot Water		
Binary - fluid cycle	300 acre-feet	1500 acre-feet
Direct steam flashing cycle	320 acre-feet	1700 acre-feet
2. Hot Rock		
Binary - fluid cycle	33 acre-feet	---
3. Steam	60 - 78 acre-feet[c]	---
	240 - 320 acre-feet[d]	---

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[a] Drilling mud effluents based on 3 acre-feet/well.

[b] Geothermal liquids are brought to the surface during drilling and testing. Reported values assume that effluents originate only from production and reserve production wells. No geothermal liquids are produced from hot rock or steam developments.

[c] Initial wells only.

[d] Due to well depletion, new wells are drilled at 14% per year. Reported value describes drilling effluent over a 30-year period.

Sources: Federal Power Commission. National Gas Survey, Volume II. Washington, D.C.: U.S. Government Printing Office. 1973, p. 74.

Jones and Stokes Associates. Geothermal Handbook. Prepared for U.S. Fish and Wildlife Service, U.S. Department of the Interior, Contract No. 14-16-008-968 U.S. Government Printing Office, June 1976, p. 155.

Additional contamination of surface and subsurface waters may occur from well blowouts. Blowouts are infrequent events caused by well casing failure. Flow of geothermal fluids from blowouts can amount to as much as 10 acre-feet per day. Blowouts can be prevented by proper design and drilling operation.[1] The frequency of blowouts at The Geysers appears to be comparable to the incidence of blowouts in New Zealand, where about 175 wells were drilled with three blowouts. The more severe blowouts occurred before 1960, and the performance record has since improved. Although blowouts can be expected to occur, the probability of a significant blowout can be reduced by technological refinements, drilling control measures, and increased operating experience.[2]

8.5.3.3 Solid Wastes

The only solid wastes generated during drilling operations are drill cuttings and mud. For a 5000-foot well, the volume of these cuttings amounts to about 0.1 acre-feet. The drilling of wells for the development of hot water systems capable of supplying 100 MW_e electric power produces 10-11 acre-feet of drill cuttings. The drilling of wells for 100 MW_e hot rock developments produces only about one acre-foot of cuttings. The initial drilling of wells for a 100 MW_e steam development produces 2-3 acre-feet of cuttings; over a 30-year period, 8-11 acre-feet are produced. These wastes are typically disposed in mud sumps, which are then dried and graded or plowed under.

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[1] Tarlock, D. and R. L. Wallar. "An Environmental Overview of Geothermal Resources Development." Geothermal Resources Development Institute. Rocky Mountain Mineral Law Foundation. Boulder, Colorado: Rocky Mountain Mineral Law Foundation, Jan. 27-28, 1977, pp. 14-5, 14-22.

[2] U.S. Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program, 4 Vols. Washington: Government Printing Office, 1973, pp. III-9, 11.

8.5.3.4 Noise Pollution

Noise levels during well drilling, cleaning, and testing have been previously described in Section 8.4.3.2. Additional noises generated during well bleeding and during blowouts are reported below:[1,2]

Operation	Duration	Noise Level	Distance
Well bleeding before power generation	Variable		
• open hole		86 dBA	5 ft
• rock-filled ditch		65 dBA	5 ft
Blowouts	Infrequent (Variable)	118 dBA	50 ft

8.5.3.5 Occupational Health and Safety Hazards

Health and safety hazards associated with geothermal drilling are principally worker exposure to toxic gases and drilling accidents. Typical drilling operations pose relatively minor hazards to crew personnel. Injuries associated with equipment operation on drill rigs are frequent but minor. Considerable danger is associated with well blowouts; however, blowouts are relatively rare occurrences.

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[1] Ecoview Environmental Consultants. Draft Environmental Impact Report for Geothermal Development of Union Oil Company's Leaseholds on the Upper Part of the Squaw Creek Drainage at the Geysers, Sonoma County, California. Napa, California: 1974.

[2] Reed, M. J. and G. E. Campbell, "Environmental Impact of Development in the Geysers Geothermal Field, U.S.A.", Proceedings of the Second United Nations Conference on the Development and Use of Geothermal Resources, San Francisco, CA, May 20-29, 1975. Washington: Government Printing Office, 1976.

Exposures to hydrogen sulfide and ammonia are believed to be the greatest potential health hazards. Both of these gases may be released to the atmosphere in highly toxic concentrations. Certain trace gases such as mercury and radon are of concern because they are toxic even at low concentrations.[1] Actual worker exposure to these gases has not been determined.

8.5.3.6 Odor

Odors at geothermal developments are chiefly associated with the presence of ammonia and hydrogen sulfide, as described in Section 8.4.3.6.

The inputs and outputs associated with each of the four geothermal developments are summarized in Table 8-31.

8.5.4 Social Controls for Obtaining Lands

Following exploration or when geothermal resources are known to exist (such as in KGRA's) the geothermal developer must comply with a series of procedures established by regulatory agencies in order to obtain rights to the lands. As indicated in the preceding sections, ownership of geothermal lands in the U.S. may be by federal or state governments, Indian tribes

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, pp. 68-71.

TABLE 8-31. SUMMARY OF INPUTS AND OUTPUTS OF DRILLING WELLS SUFFICIENT FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER

	Hot Water/Binary Cycle	Hot Water/Steam Flashing Cycle	Hot Rock/Binary Cycle	Dry Steam/Direct Use
Input Requirements				
Manpower				
• first year	150	170	17	31-40[a]
• second year	29	32	3	6-8 [a]
Materials				
• steel	18,000 tons	20,000 tons	2,000 tons	15,000-20,000 tons[b]
Economics	$43 million[c]	$47 million[c]	$13 million[c]	$20-26 million[d,e] $80-106 million[f]
Water	290 acre-ft	310 acre-ft	32 acre-ft	58-75 acre-ft[e] 230-310 acre-ft[f]
Land				
• temporarily disturbed	98 acres	108 acres	11 acres	20-26 acres[e] 80-106 acres[f]
• required for well spacing	990-4000 acres	1100-4300 acres	110-440 acres	800-1000 acres[e] 3200-4200 acres[f]
Ancillary Energy	8.9 MM gal diesel fuel	9.7 MM gal diesel fuel	1 MM gal diesel fuel	1.8-2.3 MM gal diesel fuel[e] 7.2-9.5 MM gal diesel fuel[f]
Outputs				
Air Emissions				
• diesel generators				
carbon monoxide	450 tons	490 tons	50 tons	92-120 tons[e] 370-480 tons[e]
hydrocarbons	170 tons	180 tons	19 tons	34-43 tons[e] 130-180 tons[f]
nitrogen oxides	2100 tons	2300 tons	230 tons	420-540 tons[e] 1700-2200 tons[f]
aldehydes	31 tons	34 tons	3.5 tons	6.3-8.1 tons[e] 25-33 tons[f]
sulfur oxides	140 tons	150 tons	15 tons	28-36 tons[e] 110-150 tons[f]
particulates	150 tons	160 tons	17 tons	30-39 tons[e] 120-160 tons[f]
carbon dioxide	96,000 tons	100,000 tons	11,000 tons	19,000-25,000 tons[e] 78,000-100,000 tons[f]

(Continued)

TABLE 8-31. SUMMARY OF INPUTS AND OUTPUTS OF DRILLING WELLS SUFFICIENT FOR THE PRODUCTION OF 100 MW_e ELECTRIC POWER (Continued)

	Hot Water/Binary Cycle	Hot Water/Steam Flashing Cycle	Hot Rock/Binary Cycle	Dry Steam/Direct Use
from geothermal fluids[g]				
steam	1,330,000 tons	1,330,000 tons	--	1,330,000 tons
carbon dioxide	10,600 tons	10,600 tons	--	10,600 tons
ammonia	940 tons	940 tons	--	940 tons
methane	670 tons	670 tons	--	670 tons
hydrogen sulfide	670 tons	670 tons	--	670 tons
nitrogen and argon	400 tons	400 tons	--	400 tons
hydrogen	130 tons	130 tons	--	130 tons
Water Effluents				
• drilling mud	300 acre-ft	320 acre-ft	33 acre-ft	60-78 acre-ft[e] 240-320 acre-ft[f]
• geothermal fluids	1500 acre-ft	1700 acre-ft	--	--
Solid Wastes				
• drill cuttings	10 acre-ft	11 acre-ft	1 acre-ft	2-3 acre-ft[e] 8-11 acre-ft[f]
Noise Pollution				
• blowouts (infrequent)	118 dB(A)	118 dB(A)	--	118 dB(A)
• well-bleeding (open hole)	86 dB(A)	86 dB(A)	--	86 dB(A)
Occupational Health and Safety	Not Quantified	Not Quantified	Not Quantified	Not Quantified
Odors	H_2S NH_3	H_2S NH_3	Unknown	H_2S NH_3

[a] Does not include annual drilling manpower requirements.

[b] Over 30 year life.

[c] 1976 dollars.

[d] 1977 dollars.

[e] Initial.

[f] Over 30 years; includes depletion.

[g] Based on The Geysers.

or individual Indians[1], or private individuals or corporations. The procedures governing how these lands are made available vary according to the ownership.[2] The following sections describe the rules, regulations, and established procedures for obtaining lands for geothermal development in the applicable categories.

8.5.4.1 Federal Lands

The Geothermal Steam Act of 1970[3] authorizes the Secretary of the Interior to lease any public, acquired, or withdrawn lands administered by Interior, or the Department of Agriculture's Forest Service, and any lands sold by the U.S. if rights to geothermal resources were retained. If the lands are in a known geothermal resource area (KGRA), they are to be leased by competitive leasing to the highest bidder. Leases for lands not considered to be within a KGRA may be issued to the first qualified applicant on a non-competitive basis. The procedures for leasing these lands are summarized in Table 8-32.

Royalties for geothermal leases on federal lands are set at a minimum of 10 percent and a maximum of 15 percent of the amount or value of steam or any other form of heat or energy sold or utilized by the lessee. In addition, there is a royalty

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[1] Procedures for acquiring Indian Lands in the case of most resources are generally the same as those for other federal lands, except appropriate Indian authorities do have power to veto leasing decisions. However, tribally or individually-owned Indian trust or restricted lands, within or outside the boundaries of Indian reservations, were removed by Congress from geothermal leasing under Section 15(c) of the Geothermal Steam Act of 1970 (84 Stat. 1566 [1970]).

[2] In some instances, however, ownership of the land does not indicate ownership or control of the development of the geothermal resource. See Section 8.4.4.

[3] 30 U.S.C. §§ 1001 *et. seq.* (1970).

TABLE 8-32. SUMMARY OF LEASING FEATURES FOR FEDERAL LANDS

Method	Royalty/Rental	Procedures
Competitive Lease (KGRA Lands)	USGS sets royalty rate: Minimum 10% and maximum 15% of value of production; 5% on byproducts $1.00 per acre rental with provision for escalating rate: BLM	1) BLM intent to lease lands or nominations by others 2) EIS process where required 3) Application to BLM 4) Payment of one-half bonus bid 5) Review of application: BLM 6) Award of lease 7) Furnish necessary bonds, pay remainder of bonus bid, pay first year's rent 8) Submit plan of operation for USGS approval 9) Diligent development required
Non-competitive Lease (other than KGRA lands)	USGS sets royalty rate: Minimum 10% and maximum 15% of value of production; 5% on byproducts $1.00 per acre rental with provision for escalating rate: BLM	1) Operator files application, exploration plan, and pays filling fee: BLM 2) EIS process where required 3) Review of application: BLM and USGS, to determine which applications are for lands in KGRA 4) Payment of one year's rent in advance 5) Award of lease 6) Diligent development required

of 5 percent on by-products derived from production and sold or used. To encourage production, the Act also stipulates that the lessee must pay the royalties whether or not he is engaged in selling the resource.

Rental rates are set at $1.00 per acre per year. However, another provision to encourage orderly and timely development provides that beginning in the sixth year of the lease and for each year thereafter until the production of geothermal resources in commercial quantities, the lessee is subject to escalating rental rates.

Geothermal leases extend for a primary term of 10 years and, if geothermal steam is produced in paying quantities, the lease shall extend 40 years from the date of production. The lease is then subject to renewal for an additional 40 year term. The area of the lease is set at a maximum of 2,560 acres and no individual or corporation can control more than 20,480 acres per state.

8.5.4.2 State Lands

State leasing procedures are usually similar to those for federal leases. All the states make a distinction between competitive and noncompetitive bidding lands. (Montana and Wyoming permit only competitive bids.) The state laws also have provisions concerning termination of leases; suspension; transferability; and waiver, suspension, or reduction of rents and royalties which parallel the federal statute. In some respects, however, state provisions are different. For example, leases are usually for a primary term of up to 20 years, with a preferential right for renewal, in some cases, up to 99 years. (An exception is in New Mexico law which provides for an initial term of only five years, but permits five year renewals as long as the resources are produced in commercial quantities.)

State rental provisions are similar to those specified by federal statute with roughly $1.00 per acre required as the minimum. On the other hand, state royalty provisions are somewhat different. While royalties on the gross revenue on geothermal steam are similar to the 10 to 15 percent provided for in the Geothermal Steam Act, most states have a higher royalty rate (up to 10 percent) for by-products found in geothermal fluids (e.g., minerals, chemicals) than provided for in the federal Act (5 percent).

The following tables summarize the leasing procedures and terms of the leases in the six western states containing geothermal resource. Table 8-33 summarizes competitive leasing procedures, which are methods for obtaining known geothermal areas in those states. Note also that the procedures discussed in Section 8.4.4.2 for exploration of non-known geothermal areas are in reality a leasing provision. Tables 8-34 through 8-39 give the details of each state's provisions.

8.5.4.3 Private Lands

The leasing of private lands is essentially an individual transaction between the leasee and the owner of the land. However, state laws do have some impact on the terms of the arrangement since state legislation governs contractual arrangements. Even so, state statutes for regulating private mineral development are not uniform and the process of negotiation between the land owner and the developer yields a wide variety of outcomes.

Increasingly, western states view their role in operations on private lands as one of protecting the life, health, property, and public welfare, and encouraging maximum economic recovery of

TABLE 8-33. COMPETITIVE LEASING PROCEDURES FOR KNOWN AREAS

State	Bidding Factors	Designation Criteria
Arizona	Cash Bonus	Geology and/or Competitive Interest
Colorado	Specified by Land Commissioners	Specified by Land Commissioners
Montana	Cash Bonus	All Lands Competitively Leased
New Mexico	Cash Bonus	Determined by Land Commissioners
Utah	See Footnote 1	See Footnote 1
Wyoming	Specified by Land Commissioners	Specified by Land Commissioners

[1] Utah uses the cash bonus bid for lands newly opened for geothermal development, other lands are leased by application.

Source: Sacarto, D. M. State Policies for Geothermal Development. Denver: National Council of State Legislatures, November 1976, p. 48.

TABLE 8-34. ARIZONA GEOTHERMAL LEASE FEATURES[1]

Item	Statutes	Summary
Agency		Land Department
Requirements		
Fees		
Rental		\$1 per acre[2]
Royalty		Not less than 12½%
Duration		Five years and as long as producing
Bond		
Other Information		Not more than four sections confined to six miles square

[1] Arizona Revised Codes.

[2] The non-competitive lease has the rental set in the lease terms and not by statute.

TABLE 8-35. COLORADO GEOTHERMAL LEASE FEATURES[1]

	Statutes	Summary
Agency		State Land Commissioners
Requirements		
Fees		
Rental		Set in lease
Royalty		Set in lease
Duration		Set in lease; for commercial duration
Bond		
Other Information		

[1] Colorado Revised Statutes.

TABLE 8-36. MONTANA GEOTHERMAL LEASE FEATURES[1]

Item	Statutes	Summary
Agency	§81-2601	State Board of Land Commissioners
Requirements		
Fees	§81-2603	Set by board
Rental	§81-2605	$1 per acre
Royalty	§81-2605	Not less than 10% of value of steam and not more than 5% on production
Duration	§81-2604	Ten years, and so long as producing
Bond	§81-2606	Required at discretion of the Board
Other Information	§81-2611	If the geothermal developer needs water he must apply to the Board
	§81-2612	If there is a conflict between coal, oil, gas, or geothermal developers on state lands, the first issued lease has priority, but the Board may amend to fit the situation.

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[1] Montana Revised Codes, 1947.

TABLE 8-37. NEW MEXICO GEOTHERMAL LEASE[1]

Item	Statutes	Summary
Agency	§7-15-5	Commissioner of Public Lands
Requirements		
Fees		
Rental	§7-15-5	Not less than 640 acres per lease nor more than 2,560 acres. No one person may have interest in more than 25,600 acres.
Royalty	§7-15-7	10% of steam, 2-10% of mineral sales, 8% of net or energy plant on site, 2-10% of gross used for recreation, and $1 per acre--minimum royalty of $2 per acre
Duration	§7-15-11	Primary term of 5 years and renewable for another 5 years if producing
Bond	§7-15-18	Bond not less than $5,000 as set by commissioner
Discretionary Actions	§7-15-26 §7-15-18	Commissioner may withhold land from lease or require competitive bids on unknown lands. See #7 above.
Other Information	§7-15-6	Exploration is to follow the procedure above, if lands are known to be capable of commercial geothermal production the above procedure is followed but the priority goes to the highest competitive bidder.

[1] New Mexico Statutes, 1953.

TABLE 8-38. UTAH GEOTHERMAL LEASE[1]

Item	Statutes	Summary
Agency		State Land Board
Requirements		
Fees		
Rental		$1 per acre
Royalty		10% primary, 10% net byproduct
Duration		10 years and so long as producing commercially
Bond		
Other Information	§73-1-20	The Division of Water Rights may regulate geothermal wells as necessary for safety, and maximum recovery
	§40-6-5	If developer plans to drill (exploratory), the Board of Oil, Gas, and Mining has authority to require: a) security (for plugging) b) notice of intent to drill c) filing of well log
		Maximum lease 640-2,560 acres, minimum 4 acres

[1] Utah Code Annotated, 1953.

TABLE 8-39. WYOMING GEOTHERMAL LEASE FEATURES[1]

Item	Statutes	Summary
Agency		State Land Commission
Requirements		
Fees		
Rental		$2/acre
Royalty		10% primary, 5% byproduct
Duration		10 years, and so long as producing commercially
Bond		
Other Information		Minimum Lease: 640 acres Maximum Lease: 2,560 acres

[1] Wyoming Statutes.

mineral resources. In some western states the Division of Oil and Gas has been given power to regulate geothermal operations on private lands. Geothermal developers must comply with all air and water quality controls of the state. In other words, the regulations issued by the Division of Oil and Gas are similar to those applicable to state lands. Most states also have provisions for controlling the siting and operation of electric generating facilities, providing another form of state jurisdiction on private lands.

8.6 EXTRACTION: PRODUCTION

This section describes the production of geothermal fluids from completed wells. As described below, the wellhead production system collects the geothermal fluid from wells and conveys it to a power plant or other user. Certain "well stimulation techniques" are described that may be used to increase the flow of geothermal fluids or to create cracks in impermeable hot dry rock formations. The piping network (or "gathering system") that conveys the geothermal fluid to its point of use is also described.

8.6.1 Technologies

Various technologies are employed to stimulate the production of geothermal fluids from completed production wells. These technologies and the more conventional technologies used in the fluid gathering system are successively discussed below.

Well stimulation techniques may be desirable for hydrothermal systems that have initially poor formation permeability or that have diminished fluid production because of solids deposition in the formation or well.[1] Stimulation techniques include hydraulic fracturing, chemical solvents, chemical explosives, and (potentially) nuclear fracturing. Hydraulic fracturing is commonly used by gas and oil producers. It involves pumping water down wells with a pressure sufficient to crack the rocks at the bottom. These cracks extend as pumping continues.[1,2]

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[1] Ewing, A. H. "Stimulation of Geothermal Systems," Geothermal Energy. P. Kruger and C. Otte (eds.). Stanford, CA: Stanford University Press, 1973.

After a period of production, the fluid flow from a hydrothermal resource may diminish because of the deposition of solids on the well casing and in the rock formation. Deposits of minerals (mainly silica and calcium carbonate) can be removed from the well casing by re-drilling. The re-drilling can be accomplished easily with a light drilling rig. Chemical solvents injected through the well can potentially dissolve the deposited solids and restore the well to its original production.[3]

Explosives can be used to fracture impermeable rock formations and improve the flow of fluid to production wells.[4,5] Pumps placed within the well can also increase the rate of fluid extraction. These "downhole" pumps might also be used to prevent flashing of liquid-dominated fluids, reduce the potential for scaling, and maintain noncondensable gases in solution. Downhole pumps are currently being developed.[6]

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[1] Smith, M. C. "Introduction and Growth of Fractures in Hot Rock," Geothermal Energy. P. Kruger and C. Otte (eds.). Stanford, CA: Stanford University Press, 1973.

[2] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Conneticut: The Futures Group, April 15, 1975, p. 31.

[3] *Ibid.*

[4] Ramey, H. J., Jr., P. Kruger, and R. Raghaven. "Explosive Stimulation of Hydrothermal Reservoirs," Geothermal Energy. P. Kruger and C. Otte (eds.). Stanford, CA: Stanford University Press, 1973.

[5] The Futures Group, *op.cit.*

[6] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 32.

Several techniques have been proposed for recovering heat from hot rock formations. If the hot rock has a high natural permeability, a fluid may be injected through wells and circulated through the formation. The heated fluid is then recovered. Impermeable formations must first be fractured by chemical leaching, explosive fragmenting, hydraulic fracturing, or a combination of fracturing techniques. Controlled hydraulic fracturing creates a system of cracks that resembles a pancake on edge, as shown in Figure 8-8. Heat may be recovered from the fractured rock by one of three methods: the alternate injection and recovery of fluid through a single well; the continuous circulation of fluid through coaxial pipes in the same well; or the continuous flow of fluid between two or more wells. If water is used as the circulating fluid, the geothermal energy may appear at the well-head as steam, hot water, or a mixture of the two.[1,2]

Geothermal fluids are conveyed from the production wells to the point of use through a piping network known as a gathering system. As described by The Futures Group[3], the gathering system:

> ...consists primarily of insulated piping, suitably anchored to the ground and having expansion loops or bellows. It also contains cyclone separators, screens, and filters to remove rock particles and in the case of vapor-dominated reservoirs, slugs of water that occasionally are emitted from the well. Mufflers, safety valves, and steam traps are also installed.

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[1] Smith, M. C. "Dry Hot Rock Systems." Submitted to Conference on the Magnitude and Deployment Schedule of Energy Resources, Portland, Oregon, July 21-23, 1975. 8 pp.

[2] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 31.

[3] *Ibid.*

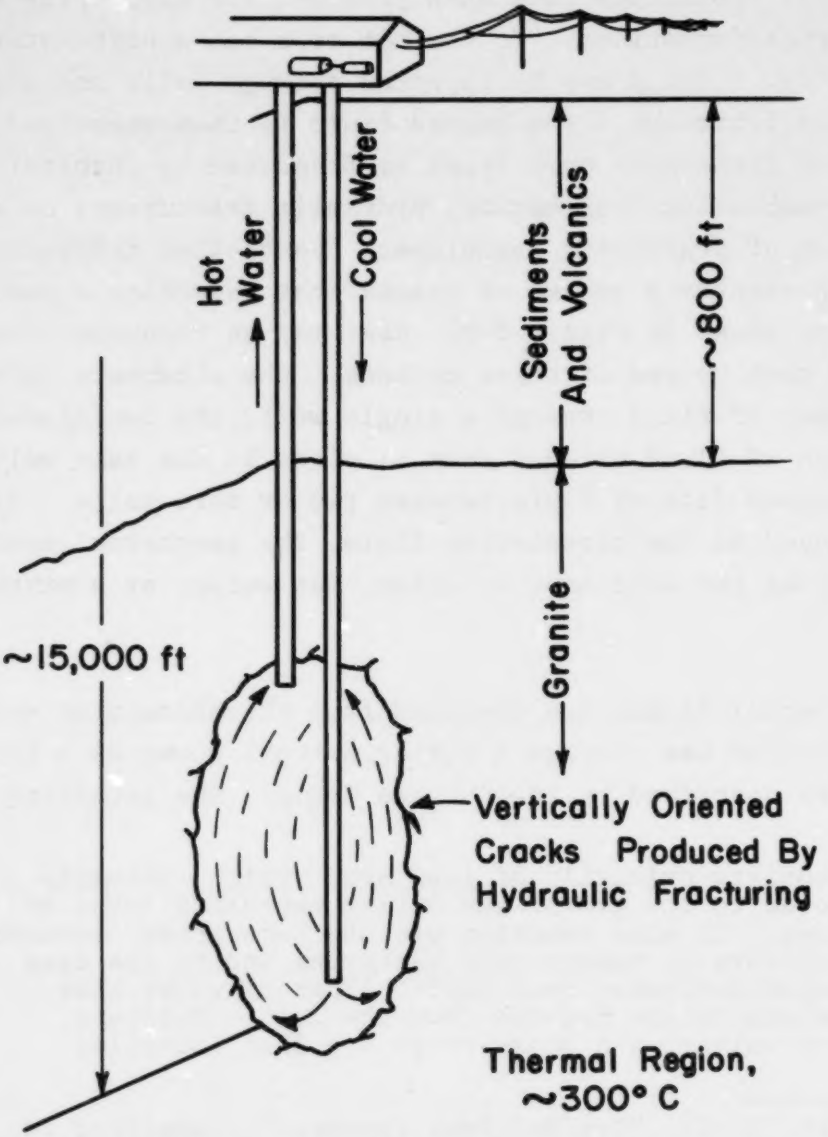
Hot Water
Cool Water
Sediments And Volcanics
~800 ft
~15,000 ft
Granite
Vertically Oriented Cracks Produced By Hydraulic Fracturing
Thermal Region, ~300° C

Figure 8-8. Dry Rock Geothermal Energy System By Hydraulic Fracturing.

Source: U.S. Atomic Energy Commission. The Nation's Energy Future; A Report to Richard M. Nixon, President of the United States, Dixie Lee Ray, Chairman. Washington: Government Printing Office, 1973.

In designing a gathering system, the objective is to maximize the flow and minimize cost and heat loss. These objectives are somewhat opposed, since large diameter piping will decrease pressure loss and maximize flow, but will also increase the surface area for heat loss, as well as pipe cost. Instrumentation useful in operating a field would include flow meters, fluid sampling equipment, and instruments for measuring the thermodynamic properties of the fluid such as temperature, pressure, and enthalpy.

Alternatives to the recovery of geothermal energy by extracting fluid from the geothermal reservoir are currently being developed. These include downhole heat exchangers, heat pipes, and direct energy conversion devices. None of these devices has been commercially demonstrated for electric power production.[1]

8.6.2 Input Requirements

Input requirements and outputs of the wellhead production system are primarily dependent on the required number of production wells. Estimated well requirements for the development of three hydrothermal and one hot rock resource have been previously reported in Section 8.5.2. In the production phase of the extraction of geothermal energy, only the required production and reserve wells are considered. These estimated well requirements are summarized in Table 8-40.

Manpower, materials and equipment, finances, water, land, and ancillary energy requirements for the recovery and transport of geothermal fluids are discussed in the following sections.

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, pp. 31-32.

TABLE 8-40. PRODUCTION AND RESERVE WELL REQUIREMENTS FOR THE GENERATION OF 100 MW_e ELECTRIC POWER[a]

Geothermal Resource Development	Required Number of Wells	
	Production	Reserve
1. Hot Water		
Binary fluid cycle	44	11
Direct steam flashing cycle	48	12
2. Hot Rock		
Binary fluid cycle	5	1
3. Steam	15-20[b]	4-5[b]
	75-100[c]	4-5[c]

[a] Summarized from Table 8-21

[b] Initial well requirements.

[c] Due to well depletion, new wells must be drilled at 14% per year. Reported value is total over 30-year period.

8.6.2.1 Manpower

Manpower requirements for the construction, operation, and maintenance of a production piping network have been prepared by Bechtel Corporation for the Federal Energy Administration.[1] Bechtel's estimates describe a piping network associated with 34 wells spaced about 1000 feet apart. Estimates reported herein are simply extrapolated from those reported by Bechtel. Bechtel's estimates of construction manpower describe the design, procurement, construction, testing, and start-up of the geothermal fluid gathering system. Table 8-41 reports the manpower required to complete the above tasks. Personnel required for the operation and maintenance of the gathering system are summarized in Table 8-42.

8.6.2.2 Materials and Equipment

Construction of the gathering system demands heavy equipment to transport and handle pipe, and to prepare pipeline corridors. None of this equipment is permanently committed to the gathering system.

Steel in the piping network is the largest material requirement of the geothermal fluid gathering system. The piping requirement is dependent on the well spacing and grid. For this analysis, an equilateral triangle grid is assumed, with wells spaced about 1000 feet apart and the power plant centrally

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[1] Federal Energy Administration, Interagency Task Force on Geothermal Energy. Project Independence Blueprint, Final Task Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974, pp. D-6,7.

TABLE 8-41. MANPOWER REQUIRED TO CONSTRUCT A GATHERING SYSTEM SUPPLYING A 100 MW_e POWER PLANT

	Manpower, total man-years				
	Hot water resource	Hot water resource	Hot rock resource	Steam resource	
Personnel Description	Binary fluid cycle	Direct steam flashing cycle	Binary fluid cycle	Initial	Over 30-year period
Design					
Mechanical engineer[a]	1.1	1.2	0.1	0.4-0.5	1.6-2.2
Civil engineer[a]	0.5	0.6	0.1	0.2	0.8-1.0
Draftsman[a]	0.5	0.6	0.1	0.2	0.8-1.0
Draftsman[a]	0.5	0.6	0.1	0.2	0.8-1.0
Route surveyor[a]	2.0	2.2	0.2	0.7-0.9	2.9-3.9
Construction					
Civil engineer[b]	1.1	1.2	0.1	0.4-0.7	1.6-2.2
Foreman[b]	2.3	2.5	0.3	0.8-1.0	3.3-4.3
Pipefitter[b]	4.9	5.3	0.5	1.7-2.2	7.0-9.3
Welder[b]	3.2	3.5	0.3	1.1-1.5	4.6-6.2
Carpenter[b]	1.6	1.8	0.2	0.6-0.7	2.3-3.1
Concrete worker[b]	3.2	3.5	0.3	1.1-1.5	4.6-6.2
Dozer operator[b]	1.6	1.8	0.2	0.6-0.7	2.3-3.1
Truck driver[b]	3.2	3.5	0.3	1.1-1.5	4.6-6.2
Crane operator[b]	1.6	1.8	0.2	0.6-0.7	2.3-3.1
Insulation installer[b]	0.8	0.9	0.1	0.3-0.4	1.2-1.5
Inspector (construction)[b]	0.9	1.0	0.1	0.3-0.4	1.3-1.8
Inspector (nondestructive testing)[b]	1.0	1.1	0.1	0.3-0.4	1.4-1.9
TOTAL	30	33	3	11-14	43-58

[a] Based on 4-month design program

[b] Based on 8-month construction program

Source: Federal Energy Administration. Interagency Task Force on Geothermal Energy. Project Independence Blueprint Final Task Force Report: Geothermal Energy. Washington, D.C. U.S. Government Printing Office. 1974. p. D-6.

TABLE 8-42. MANPOWER REQUIRED TO OPERATE AND MAINTAIN A GATHERING SYSTEM SUPPLYING A 100 MW_e POWER PLANT

Personnel Description	Manpower, average man-years per year Hot water resource Binary fluid cycle	Hot water resource Direct steam flashing cycle	Hot rock resource Binary fluid cycle	Steam resource Direct steam cycle
Operation				
Field Operator	1.6	1.8	0.2	0.6-0.7
Routine Maintenance				
Foreman	0.2	0.2	~0	~0.1
Pipefitter	0.3	0.4	~0	~0.1
Welder	0.2	0.2	~0	~0.1
Insulation Installer	0.3	0.4	~0	~0.1
Crane Operator	0.2	0.2	~0	~0.1
TOTAL	2.8	3.2	0.3	~1.2

Source: Federal Energy Administration. Interagency Task Force on Geothermal Energy. Project Independence Blueprint Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office. 1974. p. D-6.

located.[1] Assuming an average diameter of 20 inches[2] and an average thickness of $^3/_8$ inch, the amount of steel comprising 1000 feet of pipe is estimated to be about 40 tons.[3] Assuming an additional 25 percent for supports and the like, the amount of steel comprising 1000 feet of pipe is estimated to be 50 tons. Based on this value and the assumed well spacing of 1000 feet, steel requirements for the gathering of fluids from 100 MWe hot water, hot rock, and dry steam developments are estimated to be:

Hot water resource	2700-3000 tons
Hot rock resource	430 tons[4]
Steam resource, initial	950-1300 tons
Steam resource, over 30 years	3900-5300 tons.

8.6.2.3 Economics

Milora and Tester[5] have reported cost estimating factors for the costs of piping from the wellhead to the power plant. These factors (reproduced in Table 8-43) report piping costs as a fraction of the costs for drilling and casing wells. The

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[1] Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press, 1976, p. 131.

[2] Various sources indicated pipe diameters of ten to thirty-six inches; several sizes are used in each gathering system.

[3] Perry, R. H. and C. H. Chilton (eds.). Chemical Engineers' Handbook. 5th Edition. New York: McGraw-Hill Book Company, 1973, p. 6-66.

[4] Based on thirty-inch pipe diameter.

[5] Milora, S. L. and J. W. Tester, *op.cit.*, pp. 80, 131.

TABLE 8-43. COST ESTIMATING FACTORS FOR PIPING AS A FUNCTION OF DRILLING COSTS[a]

	Piping cost as a fraction of well cost[b]		
Number of wells	Vapor-Dominated	Liquid-Dominated	Dry Hot rock[c]
1 - 6	0.15	0.16	0.17
7 - 18	0.23	0.24	0.25
19 - 36	0.32	0.34	0.36
37 - 60	0.42	0.44	0.46
61 - 90	0.47	0.49	0.51
> 90	0.48	0.50	0.52

[a] Costs include labor, and describe piping from well-head to power plant. Assumes an equilateral triangle grid with an average well spacing of 200-300m and the power plant centrally located. Includes re-injection wells.

[b] Variations between liquid- and vapor-dominated and dry hot rock systems depend on items such as insulation, pipe wall thickness, materials used, 2-phase vs. 1-phase flow, gaseous effluents, and pressure losses.

[c] Assumes a pressurized-water circulating fluid.

Source: Milora, S.L. and J.W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press. 1976. p. 80.

factors are based on the total number of wells drilled, including those intended as re-injection wells. To estimate the costs of only the gathering system, one must scale the total costs of piping by the number of production and reserve wells. For example, the dry rock development requires the drilling of 11 wells, including five required for injection. The applicable piping cost factor from Table 8-43 is 0.25: total costs for piping in this development are 25 percent of the drilling and casing costs. Costs for the gathering system are estimated as $^{6}/_{11}$ of the total piping cost.

Using the method illustrated above, one can calculate the costs for each of the proposed developments. These preliminary cost estimates are tabulated in Table 8-44, and are based on drilling costs from Section 8.5.3.2.

8.6.2.4 Water

No water is required for conveying geothermal fluids to a power plant or other user. Certain well stimulation techniques (e.g., hydraulic fracturing) have significant but unknown water requirements. The stimulation of hot dry rock formations requires make-up water for use as circulating fluid, and in current tests, for fracturing the rock formation. The geothermal fluid flow in a 100 MW_e hot dry rock development has been estimated as 1450 lb/sec[1] (46 acre-feet per day). Assuming a fluid loss of 5 to

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[1] Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press, 1976, p. 102.

TABLE 8-44. ESTIMATED COSTS OF WELL-HEAD PRODUCTION SYSTEMS SUPPLYING A 100 MW_e POWER PLANT[a]

Geothermal resource development	Cost of well-head production system
1. Hot water	
Binary-fluid cycle	\$12,000,000
Direct steam flashing cycle	\$13,000,000
2. Hot Rock	
Binary-fluid cycle	\$ 1,800,000
3. Steam	\$ 6,100,000-\$ 8,000,000[c]
	\$37,000,000-\$50,000,000[d]

[a] 1976 Dollars.

[b] Based on method described in text.

[c] Initial cost.

[d] Cost over 30-year period, based on well depletion rate of 14% per year.

Source: Milora, S.L. and J.W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press. 1976.

to 10 percent,[1,2] make-up water requirements are estimated as 2½ to 5 acre-feet per day.

8.6.2.5 Land

From discussions with drillers, Anglin[3] has concluded that one-half acre per well is permanently committed to geothermal fluid recovery and transmission to a power plant or other user. Included in the above estimate are land areas required for the geothermal fluid piping network, service roads, pumps, standby generators and the like. Based on the number of production and service wells required to supply a 100 MW power plant, the following areas are assumed to be permanently committed to the wellhead production network:

Hot water resource	28-30 acres
Hot rock resource	3 acres
Steam resource, initial	9-13 acres
Steam resource, over 30 years	39-53 acres.

8.6.2.6 Ancillary Energy

Fluids from most geothermal reservoirs are free-flowing; thus, no ancillary energy is required for transporting the

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[1] Initial tests indicated loss of 15 percent of injected water; the recovery rate is expected to improve as the system is operated.

[2] Mortensen, J. J. "The LASL Hot Dry Rock Geothermal Energy Development Project." LASL Mini-Review. July 1977.

[3] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976. pp.31, 35, 37.

geothermal fluids to the energy user. Quantities of energy required for certain fracturing techniques, and for down-hole and surface pumping of low-pressure resources or for maintenance of one-phase flow are highly variable and have not been included.

8.6.3 Outputs

Only a few residuals are associated with the recovery and transport of geothermal fluids to an energy user. These residuals are discussed in the following sections as air emissions, water effluents, solid wastes, noise pollution, occupational health and safety hazards, and odor.

8.6.3.1 Air Emissions

During normal operations, no gas streams are vented to the atmosphere from the transport of geothermal fluids. Fugitive emissions of geothermal vapors and gases exist, but have not been quantified. During plant upsets or shutdowns, essentially all vapors and gases are vented to the atmosphere. These emissions are similar to those during production testing, as previously described in Section 8.5.3.1. Quantities emitted during upsets are unknown.

8.6.3.2 Water Effluents

During the recovery and transport of geothermal fluids, there are no water effluents from the well production and piping network. Some potential exists for the contamination of ground water as the geothermal fluid is transported up the production well. However, this potential hazard can be reduced to insignificance by proper and complete casing of the production wells. Rupture of the piping network is rare, but can be a source of contamination of surface water.

A small waste effluent may be associated with the removal of solids and particulates from the geothermal fluids. This effluent has not been quantified but is probably less significant than other effluents occurring during geothermal energy development.

8.6.3.3 Solid Wastes

The only solid wastes generated from the wellhead production system are those solids and particulates removed from the geothermal fluids at the wellhead. Quantities of these wastes have not been estimated.

8.6.3.4 Noise Pollution

During normal operation, little noise is associated with the wellhead production system. Noise levels from a muffled steam line vent during plant upsets have been reported to be 90 dBA at a distance of 100 feet. During a rare rupture of a steam line, noise levels of 100 dBA at a distance of 50 feet are anticipated.[1]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 65.

8.6.3.5 Occupational Health and Safety Hazards

Safety hazards associated with the operation and maintenance of the wellhead production system are likely to be relatively minor. Health hazards are chiefly associated with worker exposure to toxic gases including H_2S and NH_3. These have been previously described in Section 8.5.3.5.

8.6.3.6 Odor

Odors at geothermal developments are chiefly associated with the presence of ammonia and hydrogen sulfide, as described in Section 8.5.3.6. Odor levels of these gases in the proximity to wellhead production systems have not been reported.

The inputs and outputs associated with the wellhead production system are summarized in Table 8-45.

8.6.4 Extraction Social Controls

The extraction and development of geothermal resources is regulated by federal, state, and local government. At each of these levels, laws, regulations, rules and other policies have been enacted that directly or indirectly affect the deployment of geothermal extraction-drilling-production technologies. The resulting regulatory system can be classified under four basic headings: planning and land-use activities including the environmental impact statement process; regulations pertaining to the health and safety of operations personnel; procedures that relate to environmental protection and land restoration; and rules established in the interest of conservation to encourage orderly and timely development of geothermal resources. These are described in several jurisdictional levels in the following sections.

TABLE 8-45. SUMMARY OF INPUTS AND OUTPUTS ASSOCIATED WITH WELLHEAD PRODUCTION SYSTEM AT A 100 MW$_e$ POWER PLANT

	Hot Water/ Binary Fluid	Hot Water/ Steam Flashing	Hot Rock/ Binary Fluid	Dry Steam/ Direct Use
Input Requirements				
Manpower				
• Construction	30 man-years	33 man-years	3 man-years	11-14 man years[a] 43-58 man-years[b]
• Operating	3 men	3 men	0.3 men	~1.2 men
Materials				
• Steel	2,700 tons	3,000 tons	430 tons	950-1300 tons[a] 3900-5300 tons[b]
Economics	$12 million	$13 million	1.8 million	$6.1-$8 million[a] $37-$50 million[b]
Water	-	-	2.5-5 acre ft/d	-
Land	28 acres	30 acres	3 acres	9-13 acres[a] 39-53 acres[b]
Ancillary Energy	None-Variable	None-Variable	Variable	None-Variable
Outputs				
Air Emissions	Small	Small	Small	Small
Water Effluents	Small	Small	Small	Small
Solid Wastes	Undetermined	Undetermined	Undetermined	Undetermined
Noise Pollution				
• Production	Little	Little	Little	Little
• Muffled Vent[c]	90 dB(A)	90 dB(A)	90 dB(A)	90 dB(A)
Occupational Health and Safety	Not Quantified	Not Qualtified	Not Quantified	Not Quantified
Odor	NH_3 H_2S	NH_3 H_2S	Unknown	NH_3 H_2S

[a] Initial

[b] Over 30 years

[c] At 90 feet

8.6.4.1 Federal Planning and Land Use

The Geothermal Steam Act of 1970 excluded certain public, acquired, and Indian lands from the leasing program because of their special land values or other unique characteristics. These include: 1) lands administered by the National Park Service; 2) lands within national recreation areas; 3) lands used for fish hatcheries; wildlife refuges, wildlife or game range lands, wildlife management areas, waterfowl production areas, or lands reserved to protect endangered species; and for tribally or individually owned Indian trust or restricted lands. Lands administered by the Department of Agriculture, and lands withdrawn under the Federal Power Act may be leased only with the consent of the administering agency and under the terms stipulated by the agency.

Prior to a lease sale of geothermal lands, BLM must prepare an environmental impact statement if the Director of the agency determines that issuance of the lease would be a major federal action under NEPA provisions. In so doing, the agency must:

> evaluate fully the potential effect of the geothermal resources operations...on the total environment, fish and other aquatic resources, wildlife habitat and populations, aesthetics, recreation and other resources in the entire area during exploratory, developmental, and operational phases...(including) the potential impact of the possible development and utilization of the geothermal resources including the construction of power generating plants and transmission facilities on lands which may or may not be included in a geothermal lease.[1]

In this evaluation process, BLM must request and consider the views and recommendations of all concerned federal agencies;

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[1] 43 C.F.R. 3200.0-6, 38 Fed. Reg. 35084 (1973).

may hold public hearings; and as appropriate consult with state agencies, organizations, industries, and lease applicants. A potential factor explicitly stated for consideration is the use of the land and its natural resources consistent with federal multiple-use management principles.[1] If a decision is then made to lease, the regulations require that BLM provide "special terms and conditions to be included in (the lease) as required to protect the environment, to permit use of the land for other purposes, and to protect other natural resources."[2] Although framed in discretionary terms, these provisions appear mandatory when viewed in conjunction with the National Environmental Policy Act.

The above environmental analysis process generally takes place prior to the issuance of an exploration permit on KGRA or competitive lease lands. Generally, an environmental impact statement is not required for exploration on non-competitive geothermal lands. A programmatic impact statement has been issued which covers all geothermal exploration.

If the developer acquires a lease, he is then in a position to begin developmental drilling. According to applicable regulations, this drilling process requires clearances by USGS regarding drilling plans and proposals, and compliance with applicable state laws.

8.6.4.2 State Planning and Land Use

Although most states in the west regulate development of geothermal resources, only five states have requirements for reservoir management. Agencies in each of these states are given the authority to ensure that development operations do not needlessly degrade other natural resources of the state and that the resources are not wasted.[1] This section will summarize these regulations.

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[1] 30 C.F.R. 270.11, 270.15 (f), 38 Fed. Ref. 35069 (1973).

[2] 38 Fed. Reg. 35084 (1973), 43 C.F.R. 3200.0-6.

Faced with depletion problems similar to those in oil and gas production, the states have given their agencies at least one of three management techniques. These include well-spacing and pooling, direct production restrictions, and provisions for the unit operation of reservoirs.

The well-spacing regulations require that the wells be spread out to a minimum surface area per well (e.g., 40 acres/well). Additional regulations might require that the wells be a certain distance from the property line, buildings, roads, or other wells. A regulated regulatory method is that allowing "pooling" of separate properties. When a resource owner acquires control of land which does not total the minimum necessary for an individual well, by statute he can join a neighbor to reach the minimum. In a few states "forced pooling" is allowed.

If direct production restrictions apply, the administering state agency determines the maximum efficient withdrawal for the reservoir and then prorates the amount in accordance with the development interests. Over-production of a reservoir can result in a reduction of ultimate reservoir productivity.

A final type of regulation allows the reservoir owners to unitize; that is, to produce the reservoir as a whole. Under unitization each producer benefits from increased efficiency and therefore spacing and production rates are actively and voluntarily pursued. This reduces the regulatory burden on states.[1] Table 8-46 summarizes the regulatory tools used in the West to allow for reservoir management.

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[1] Sacarto, Douglas M., State Policies for Geothermal Development. Denver: National Conference of State Legislatures, November, 1976, p. 55.

TABLE 8-46. REGULATORY MECHANISMS IN THE STATES FOR GEOTHERMAL DEVELOPMENT

State	Area Spacing	Pooling	Unitization	Production Restrictions
Arizona	X	X	X	-
Colorado	X	X	-	-
Montana	-	-	-	-
New Mexico	X	X	-	X
Utah	X	-	-	-
Wyoming	X	-	-	X

Source: Sacarto, Douglas M., State Policies for Geothermal Development. Denver: National Conference of State Legislatures, November, 1977, p. 55.

8.6.4.3 Health and Safety

Both state and federal statutes contain provisions for safeguarding the life and health of workers and the public. BLM includes provisions with respect to public safety as part of the conditions for awarding geothermal leases. USGS enforces its own stipulations regarding public safety and human health and safety in operations conducted under BLM geothermal leases. In addition, the Occupational Safety and Health Administration (OSHA) promulgates and enforces worker health and safety regulations in areas not regulated by other federal agencies.

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[1] Sacarto, Douglas M., State Policies for Geothermal Development. Denver: National Conference of State Legislatures, November, 1977, p. 55.

At present, major occupational health and safety considerations for geothermal extraction technologies parallel those of the oil and gas drilling system. This is largely because current drilling equipment, technology, and methods are similar to those used in oil and gas operations, with modifications to suit the specific geothermal drilling needs. However, it is also in part due to the limited state of development of geothermal resources as a whole. Other necessary standards will probably become more clearly defined as additional exploratory and extraction drilling is undertaken.

During test drilling and subsequent production testing, the possibility of a blowout, in which steam or hot water escape uncontrolled, poses a hazard which can jeopardize the health and safety of employees.[1] As a result, the lessee is required by USGS to select the kinds of equipment (e.g., weights and types of drilling fluids and provisions for controlling fluid temperatures, blowout preventers, other surface control equipment, casing and cementing materials, etc.) to keep all wells under control at all times, thereby insuring the safety of life and property.[2] Also, specific requirements related to accident prevention may be included in the terms of the lease or in Geothermal Resources Operational (GRO) Orders issued by the Supervisor. Operating regulations provide that all accidents (including accidents involving blowouts) on leased land be reported to the Supervisor within 24 hours and that full reports be submitted within 15 days.[3]

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[1] A blowout at the Geysers field in California has remained uncontrolled for several years because of the danger and expense to cap the well.

[2] 30 C.F.R. 270.40, 38 Fed. Reg. 35070-35071 (1973).

[3] 30 C.F.R. 270.46, 38 Fed. Reg. 35071 (1973).

A related serious health hazard is the sound level of noise from steam ejection or expansion due to accidental blowout or during the venting of steam wells after completion. Operating regulation 240.42 specifies that the welfare of employees and the public must not be affected as a consequence of the "noise created by the expanding gases." Federal occupational noise exposure levels applicable to geothermal operations have been established,[1] as well as permissible noise exposure based on the sound level duration in hours per day. Besides the federal standards, many states have enacted occupational noise standards to protect workers. If such state standards are more restrictive than federal standards, they will apply to geothermal activity in lieu of federal standards.[2] It is a USGS function to approve the method and degree of noise abatement adopted by the lessee.

Noise regulation associated with geothermal development is imposed by the BLM on federal leases. All geothermal developers are subject to local noise ordinances, but only one county has specifically directed regulations at geothermal development.[3]

Production testing, which is the transitional phase between exploration and potential development and production, involves venting of the geothermal well to the atmosphere, with accompanying vapor release and, as noted above, noise. This vented steam often contains (in varying amounts) noncondensable gases such as carbon dioxide, methane, hydrogen, nitrogen, argon, carbon monoxide, hydrogen sulfide, radon, ammonia, and vapors such as boron and mercury.[1] The toxicity of these gases varies, but at least one potential hazard would be both the toxicity and nuisance odor of hydrogen sulfide. Under normal climatic and topological conditions, hydrogen sulfide would mix with the atmosphere and would not tend to accumulate locally. However, under stagnant air or temperature inversion conditions, the gas could accumulate locally to a high nuisance level, and perhaps a toxic level.[2] Under extreme conditions, some of the other gases present in geothermal fluids could pose similar threats to operating personnel. As a result, during production testing, considerable monitoring and analytical work is required for evaluating the potential risk and for establishing control measures needed to assure that federal and state public health and safety requirements are met.

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[1] 29 CFR 1910, Section 6(a) and 8(g).

[2] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973, p. III-62.

[3] Although not part of this study, Imperial County, California has a noise abatement component to its geothermal ordinance.

An additional health and safety hazard encountered during field development is the use of asbestos, alone and in combination with fiberglass, as insulation material around pipelines, as a sheathing material on cooling towers, and for various other purposes. If airborne asbestos fibers are sufficiently concentrated in enclosed fabricating and storage areas, and are inhaled by workers, they could pose a health hazard. Thus, as with noxious gases, monitoring is required at fabrication and storage areas and during field installation to assure health and safety protection.[3]

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[1] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973, p. III-11.

[2] *Ibid.*, p. III-14.

[3] *Ibid.*, p. III-27.

8.6.4.4 Environmental Protection and Restoration

Alleviation of potential environmental impacts resulting from geothermal exploration and development operations is accomplished under the applicable federal, state, and local laws and regulations, geothermal leasing and operating regulations, Geothermal Resources Operational (GRO) Orders issued by the Supervisor (an authorized representative of the Secretary of the Interior), and other lease and land-use permit provisions. Section 8.5.4.1 above described the provisions for initial environmental analysis as specified in the leasing regulations. In addition to these procedures which establish the framework within which all exploration and development operations are to be conducted, specific environmental protection measures are included throughout the regulations. These will be discussed below.

General Considerations

The basic federal requirement is that lessees (including operators) take all reasonable precautions to prevent any environmental pollution or damage, including damage to trees, other vegetation, natural resources, fish and wildlife and their habitat.[1] In addition, a subsequent section provides that geothermal developers must comply with all "federal and state standards with respect to the control of all forms of air, land, water, and noise pollution, including, but not limited to, the control of erosion and the disposal of liquid, solid, and gaseous wastes.[2] This section also grants the Supervisor discretionary authority to establish additional and more stringent standards which must be met.

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[1] 30 C.F.R. 270.30, 38 Fed. Reg. 35069 (1973).

[2] 30 C.F.R. 370.41, 38 Fed. Reg. 35071 (1973).

Environmental problems and impacts stemming from geothermal resources development are to be mitigated as indicated under operating regulations.[1] The former Section (30 CFR 270.11) gives the Supervisor authority to issue written GRO orders to implement regulations insuring protection of the environment, while the latter Section provides, among other things, that authorized field officials of Interior shall inspect and supervise geothermal operations to insure implementation of regulations to prevent unnecessary damage to natural resources, to prevent degradation of water quality, and to protect air, water and other environmental qualities.[2] This includes inspection and control of activities which might cause subsidence of the land surface to determine if the potential subsidence is unacceptable. The Supervisor may also prescribe or approve variances from previous GRO orders when necessary for environmental protection.[3] Stipulations regarding emissions and effluents issued by USGS, BLM, and other concerned agencies are enforced by USGS. Also the Forest Service and the Bureau of Sport Fisheries and Wildlife (BSFW) can make recommendations concerning emission and effluent stipulations to be included in BLM geothermal leases and to be enforced by USGS.[4]

Air Quality

The basic provisions for air pollution control are included in the leasing regulations, Sections 3204.1 (c) (3), 3204.1 (c) (5), and 3210.2-1, and in the operating regulations, Section

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[1] 30 C.F.R. 270.11 and 270.12.

[2] 38 Fed. Reg. 35069 (1973).

[3] 30 C.F.R. 270.48, 38 Fed. Reg. 35071 (1973).

[4] Doub. Federal Energy Regulation. 1974: H-28.

270.30, 270.40, 270.41, and 270.46. Geothermal development must also conform to various federal guidelines dealing with air quality as established by EPA. State ambient air quality standards are likewise applicable.[1] In those western states with potential for geothermal development, air quality standards for the most part apply only to carbon monoxide and particulates (some states have, however, promulgated standards for dust and hydrogen sulfide). In addition to these ambient criteria, any geothermal development that occurs in certain designated state air basins must comply with any additional standards for that basin.[2]

Only one national standard could potentially be violated by geothermal development: the National Primary Standard for carbon monoxide of 10 milligrams per cubic meter for a maximum eight hour concentration not to be exceeded more than once per year.[3]

The main air pollutant emitted during geothermal operations/ development is hydrogen sulfide. As of January 1977, of the eight western states, Montana, New Mexico, North Dakota, and Wyoming had set hydrogen sulfide standards.[4] In addition Utah's limits on sulfur compound emissions may pose some limitations upon geothermal development.[5] However, other states could easily limit hydrogen sulfide pollutants by the use of odor regulations[1] specifically or by a common law nuisance action.

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[1] In a recent case the U.S. Supreme Court held that EPA must enforce state standards on federal activities through EPA's regulations - this being true fro air or water regulations. See Hancock vs. Train. 426 U.S. 167 (1976), and EPA vs. California ex rel Water Resources Board. 426 U.S. 200 (1976).

[2] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973, p. III-54.

[3] U.S. Clean Air Act Amendments of 1970.

[4] Tarlock, A. Dan, and Richard L. Waller. "An Environmental Overview of Geothermal Resources Development." Geothermal Resources Development Institute. Boulder, Colorado: Rocky Mountain Mineral Law Foundation, 1977, p. 14-31.

[5] *Ibid.*

Water Quality

With respect to water resources, Section 3204.1 (c) (2) of the leasing regulations and Section 270.41 of the operating regulations for geothermal development require lessees (including operators) to conduct all activities in compliance with federal and state water quality standards. Geothermal leasing regulations further specify: "Toxic materials shall not be released into any surface waters or underground waters. Reinjection of waste geothermal fluids into geothermal or other suitable aquifers will be permitted upon approval (of the Supervisor)."[2]

Water quality problems associated with geothermal development are regulated by two different methods. One type of regulatory framework is the federally guided state programs as discussed in Chapter 2. These include the FWPCA and the Safe Drinking Water Act (SDWA). The remaining method of handling water pollution is the use of common law causes of action (e.g., nuisance).

Water pollution control under the nuisance causes of action can be either by negligence or strict liability. Because the type of water pollution resulting from geothermal resource development is similar to that from oil and gas operations a comparison of social controls would be beneficial. As one source has noted, salt water disposal pit overflow or the escape of gas from a well have been held to constitute negligence and similar results could occur in geothermal.[1] The strict liability for damages has been imposed in oil and gas law only in cases of violation of duties imposed by statutes or administrative order. Brine disposal can be handled by a National Pollutant Discharge Elimination System (NPDES) permit, where the federal or state government will issue the permit if the waters are cleaned to acceptable levels.[2]

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[1] Regulations are in effect in Colorado, Montana, South Dakota, and Wyoming.

[2] 43 C.F.R. 3204.1 (c) (2), 38 Fed. Reg. 35088 (1973).

An additional problem with discharge of the brine into surface waters is the high heat content of geothermal wastes. Court interpretation of EPA's method of controlling heat discharges is not clear. EPA had banned the use of cooling lakes (where a stream flow is impounded), but in a recent case EPA was required to look again at the decision.[3] The court said the decision conflicts with the Congressional policy of conserving water in the arid West. Further the court required EPA to look at the costs and benefits derived from the required cooling technologies compared to other alternatives.

Because the reinjection of brines into the geothermal reservoir helps maintain the reservoir pressure, that is the preferred method of disposal. Further, the deep well injection avoids contamination of surface and ground waters.[4] EPA initially asserted jurisdiction over underground injection under the FWPCA but a court decision limited the jurisdiction to only injections that might cause surface water pollution.[1] Congress subsequently passed the Safe Drinking Water Act giving EPA authority to require state programs to control underground injection.[2] Regulations on underground injection have not yet been issued.

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[1] Tarlock, A. Dan, and Richard L. Waller. "An Environmental Overview of Geothermal Resources Development." Geothermal Resources Development Institute. Boulder, Colo.: Rocky Mountain Mineral Law Foundation, 1977, p. 14-23.

[2] For some discharges, effluent limitations have been established (e.g., waters pumped out of coal mines), but as of yet none have been written for geothermal development. See *ibid* pp. 14-25. In that case limitations can be set on an ad hoc basis.

[3] Appalachia vs. Train. 545 F.2d 1351, 9 ERC 1033, Modified 9 FRC 1974 (4th Cir. 1976).

[4] Federal geothermal lessees can be allowed by the BLM geothermal supervisors to use reinjection. 40 CFR S 124.80, 125.26 (1975).

State control of geothermal reinjection is unclear. Since the FWPCA required the states to include a provision in their laws to allow control of underground injection prior to EPA approval of their program, the states of Colorado, Montana, North Dakota, and Wyoming have such provisions.[3] Unfortunately, the provisions were written prior to a serious interest in geothermal development and the application is debatable. Questions which have been identified, for example, include: Is brine returned to a geothermal reservoir system a "pollutant"? Is the geothermal reservoir part of the waters of the state?[4]

Biotic Resources

In the case of biotic resources, the federal leasing regulations are flexibly written to include provisions for appropriate protection measures. Due to the diversity of vegetative cover, fish and wildlife habitats and populations, it is not possible to establish a single all-encompassing set of provisions to adequately cover all situations. However, measures to protect fish and wildlife and their habitat, and to restore all disturbed lands in an approved manner are contained in 43 CFR Section 3204.1 (g) and (i). These measures are to be established on a site-specific basis and included as special stipulations in each lease or as GRO's. Water quality measures, as discussed above, must also provide for the protection of fish and other water-related wildlife factors. Likewise, special noise control stipulations may be required if there are critical wildlife factors such as nesting, mating, migration routes, to be considered for the area under development.[1]

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[1] U.S. vs. GAF Corp.. 389 F. Supp. 1379 (S.D. Texas 1975).

[2] Eckert, EPA Jurisdiction Over Well Injection Under the Federal Water Pollution Control Act, 9 NAT. RESOURCES L. 455 (1976).

[3] See Section 2.9 of Chapter 2.

[4] Tarlock, A. Dan and Richard L. Waller. "An Environmental Overview of Geothermal Resources Development," Geothermal Resources Development Institute, Boulder; Colorado: Rocky Mineral Law Foundation, 1977, pp. 14-28.

Land Restoration

It is inevitable that lands and related vegetation will be disturbed as a result of geothermal development. Consequently, numerous provisions for the restoration of land surfaces upon abandonment or termination of geothermal activities are included in the operating and leasing regulations. Federal operating regulations stipulate that the lessee must comply with all federal and state standards with respect to land pollution, the control of erosion, and the disposal of liquid, solid, and gaseous wastes.

Proper reclamation and revegetation during development as well as at completion are stressed. For example, when no longer needed, pits and sumps are to be filled and covered and the premises restored to "a near natural state" as prescribed by the

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[1] Department of the Interior. Final Environmental Statement for the Geothermal Leasing Program. Volume I of IV. Washington, D.C.: U.S. Government Printing Office, 1973, pp. III-77, 78.

Supervisor.[1] Operating regulations further stipulate that "the premises at the well site shall be restored as near as reasonably possible to its original condition immediately after plugging operations are completed on any well, except as otherwise authorized by the Supervisor."[2]

Additional measures to rectify land damage on federal lease are contained in the leasing regulations. Section 3204.1 (i)[3] requires restoration of all disturbed lands; Section 3244.1 (2) (a) provides that upon relinquishment of a lease, a statement must be submitted as to whether the relinquished land has been disturbed and whether it was restored according to the terms of the lease; and Section 3204.1 (d) additionally requires that the developer remove or dispose of all waste, including but not limited to, human waste, trash, garbage, refuse, petroleum products, and extraction and processing waste generated in connection with the operation, in a manner acceptable to the Supervisor. GRO orders may be issued as necessary to entail specific land reclamation activities not covered in the leasing or operating regulations. Site-specific revegetation methods may also be specified by GRO order or lease stipulation.

Well Abandonment

Notice of intention to abandon any well (whether a drilling well, geothermal resources well, water well, or dry hole) must be filed with and approved by the Supervisor. Operating regulations require that the lessee shall "promptly" plug and abandon any well that is not used or useful. Abandonment work must be conducted so as to preserve fresh water aquifers and prevent the intrusion of saline or polluted waters into these aquifers. After work is completed, the operator has 30 days to file a report of abandonment.[1]

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[1] 30 C.F.R. 270.44, 38 Fed. Reg. 35071 (1973).

[2] 30 C.F.R. 270.45, 30 Fed. Reg. 35071 (1973).

[3] Of Chapter 43, Code of Federal Regulations.

8.6.4.5 Conservation

Both federal and state statutes emphasize avoiding waste during geothermal extraction and development. In terms of resource conservation, the Secretary has broad authority under federal laws and regulations to withdraw or otherwise exclude certain public lands from leasing and development.[2] BLM under its operational regulations is authorized and directed to "ensure that all operations, within the area of operations, will conform to the best practice and are conducted in such manner as to protect the deposits of the leased lands and to result in the maximum ultimate recovery of geothermal resources, with minimum waste..."[3] In addition, Section 3204.2 of the leasing procedures requires that the lessee (including operators) use all reasonable precautions to prevent waste of geothermal and other natural resouces found or developed in the area of the lease.

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[1] 30 C.F.R. 270.45 and 270.72 (f) (f), 38 Fed. Reg. 35071-35072 (1973).

[2] 43 C.F.R. 3201.1-2, 38 Fed. Reg. 35014 (1973).

[3] 30 C.F.R. 270.11, 38 Fed. Reg. 35069 (1973).

8.7 USES OF GEOTHERMAL ENERGY

Estimates of the near-term development potential of geothermal energy vary widely. One view holds that geothermal energy is most important for electricity generation, but only in certain local areas or in under-developed countries seeking alternatives to even more expensive energy sources. The counterview holds that geothermal energy has the greatest potential in direct thermal or other non-electric applications.[1]

In 1976, electricity generating capacity from geothermal resources amounted to about 1360 MW_e worldwide.[2] Worldwide, the largest non-electric uses of geothermal energy were heating and irrigation in greenhouses, representing over 5500 MW_t average energy consumption.[3]

This chapter describes both electric and non-electric use of geothermal energy. Alternatives for electric power generation are discussed in Section 8.7.1. Input requirements and outputs for power generation are discussed in Sections 8.7.2 and 8.7.3 respectively. The numerous direct thermal or other uses of geothermal energy are discussed in Section 8.7.4.

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 3.

[2] Meidav, T., S. Sanyal, and G. Facca. "An Update of World Geothermal Energy Development." Geothermal Energy Magazine. 5(5): 30-34, May 1977.

[3] Howard, J.H. "Principal Conclusions of the Committee on the Challenges of Modern Society Non-Electrical Applications Project." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA. May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office. 1976. pp. 2127-2139.

8.7.1 Electric Power Generation

There are essentially five conversion technologies for the production of electricity from geothermal fluids:

- dry steam system
- flashed steam system
- binary cycle system
- hybrid flashed steam/binary cycle system
- total flow system.

Features of each system are discussed in the following sections.

8.7.1.1 Dry Steam System

A simplified schematic for the production of electricity from a geothermal dry steam resource is shown in Figure 8-9. Dry steam systems are currently producing electricity on a commercial scale in the United States, Italy, and Japan. At the Geysers in Sonoma County, California, Pacific Gas and Electric Company is producing over 500 MW_e from a dry geothermal steam. This represents the only commercial use of geothermal energy for electricity generation in the United States. By 1985, production at The Geysers is expected to increase to 1800-2130 MWe, comprising 50-60 percent of the estimated geothermal power production in the U.S.[1]

The geothermal steam from production wells requires only minor pretreatment prior to use. This pretreatment usually

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[1] La Mori, Phillip N. "Growth in Utilization of Hydrothermal Geothermal Resources." Geothermal Resources Council, Transactions, Vol. 1, May 1977. pp. 181-182.

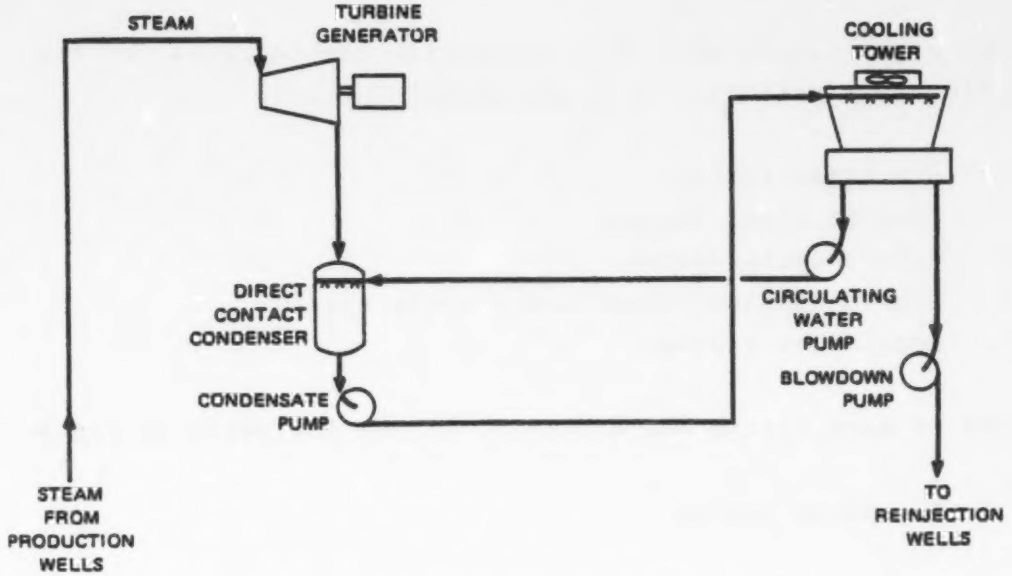
STEAM
TURBINE GENERATOR
COOLING TOWER
DIRECT CONTACT CONDENSER
CIRCULATING WATER PUMP
BLOWDOWN PUMP
CONDENSATE PUMP
STEAM FROM PRODUCTION WELLS
TO REINJECTION WELLS

Figure 8-9. Simplified Schematic of a Dry Steam Energy Conversion System

Source: Ramachandran, G. et al. Economic Analyses of Geothermal Energy Development in California, 2 Vols. Stanford Research Institute. Prepared for U.S. Energy Research and Development Administration and California Energy Resources Conservation and Development Commission. Contract No. ERDA/SAN E(04-3)-115-P.A.108. May 1977. p. 30.

entails the removal of particulate matter and occasional slugs of water. The cleaned steam is expanded in a conventional low-pressure steam turbine which then powers a generator to produce electricity. Although steam could be exhausted from the turbine directly to the atmosphere, a condenser is normally employed to increase turbine efficiency and avoid the condensation of steam in the turbine. Either a direct contact condenser or a surface condenser can be used to condense the exhaust steam. In surface condensers, the coolant does not contact the vapor or condensate: condensation occurs on a wall separating the coolant and the vapor. Contact condensers usually cool the vapor by spraying the coolant directly into the gas stream. Contact condensers also act as scrubbers in removing vapors which normally might not be condensed. Heat rejection systems such as cooling towers provide cooling water for the condensers.[1]

To maximize the energy extraction of the power cycle and to avoid the condensation of steam in the turbine, a vacuum is maintained in the exhaust steam condensers. Noncondensable gases including in-leakage air, which limit the vacuum that can be maintained, are removed with gas ejectors: either multi-stage steam jets or centrifugal exhausts are typically employed.[2]

Direct contact condensers are currently used in those dry steam systems that condense turbine exhaust steam.[3] Noncondensable gases removed with gas ejectors are simply released to the atmosphere. At The Geysers, a program is planned in which a ducting system will be installed on all existing units to transfer the gases from the gas ejectors to the cooling towers. Proposed air pollution control techniques to be applied at the cooling towers are discussed in Section 8.7.3.1.[1] Future generating units built at The Geysers will employ surface condensers to condense turbine exhaust steam.[2]

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 32.

[2] Axtmann, R. C. "Emission Control of Gas Effluents from Geothermal Power Plants." Environmental Letters 8(2): 135-146 (1975).

[3] *Ibid.*

No external makeup water is required for cooling at The Geysers: all cooling water is supplied by condensed turbine exhaust steam.[3,4]

Current generating units at The Geysers are relatively small; an average plant supplies 110 MW_e electric power and consists of two 55-MW_e generators. About two million lb/hr of steam at 350°F and 100 psi enter the turbines at each plant.[5]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 79.

[2] Ramachandran, G., et al. Economic Analyses of Geothermal Energy Development in California, 2 Vols. Stanford Research Institute. Prepared for U.S. Energy Research and Development Administration and California Energy Resources Conservation and Development Commission. Contract No. ERDA/SAN E(04-3)-115-P.A. 108. May 1977 p. 41.

[3] Axtmann, R. C. "Emission Control of Gas Effluents from Geothermal Power Plants." Environmental Letters 8(2): 135-146 (1975). p. 141.

[4] Resource Planning Associates, Inc., *op.cit.*, p. 60.

[5] *Ibid.*, pp. 19-20.

Plants larger than 100 MW_e are not anticipated.[1,2] The overall plant efficiency for power production from geothermal steam is approximately 14 to 16 percent, compared to 32 to 34 percent for nuclear power production and 36 to 40 percent for production from fossil fuels.[3]

8.7.1.2 Flashed Steam System

A simplified schematic for the production of electricity from a geothermal hot water or liquid-dominated resource is shown in Figure 8-10. Plants employing the flashed steam process are in operation or under construction in New Zealand, Mexico, Japan, the Philippines, Central America, and Iceland. The largest of these facilities is located at Wairakei, New Zealand, with an installed power generating capacity of 190 MW_e. A flashed steam plant at Cerro Prieto, Mexico, has an electric power production capacity of 75 MW_e.[4] No commercial flashed steam plants have been built in the United States.

If the pressure of a liquid-dominated geothermal fluid is not maintained as the fluid is withdrawn from a well, the

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, pp. 53, 56.

[2] Larger plants must be supplied with steam from wells located greater distances from the site of power generation. As the plant size increases, the increased costs of the piping network become more important than economies of scale associated with larger units.

[3] Uranesh, G. and J. D. Musick, Jr. "Geothermal Resources: Water and Other Conflicts Encountered by the Developer." Geothermal Resources Development Institute. Rocky Mountain Mineral Law Foundation, Boulder, Colorado. January 27-28, 1977, p. 6-10.

[4] Muffler, L. J. P. "Summary of Section I: Present Status of Resources Development." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. xxxiii-xlv.

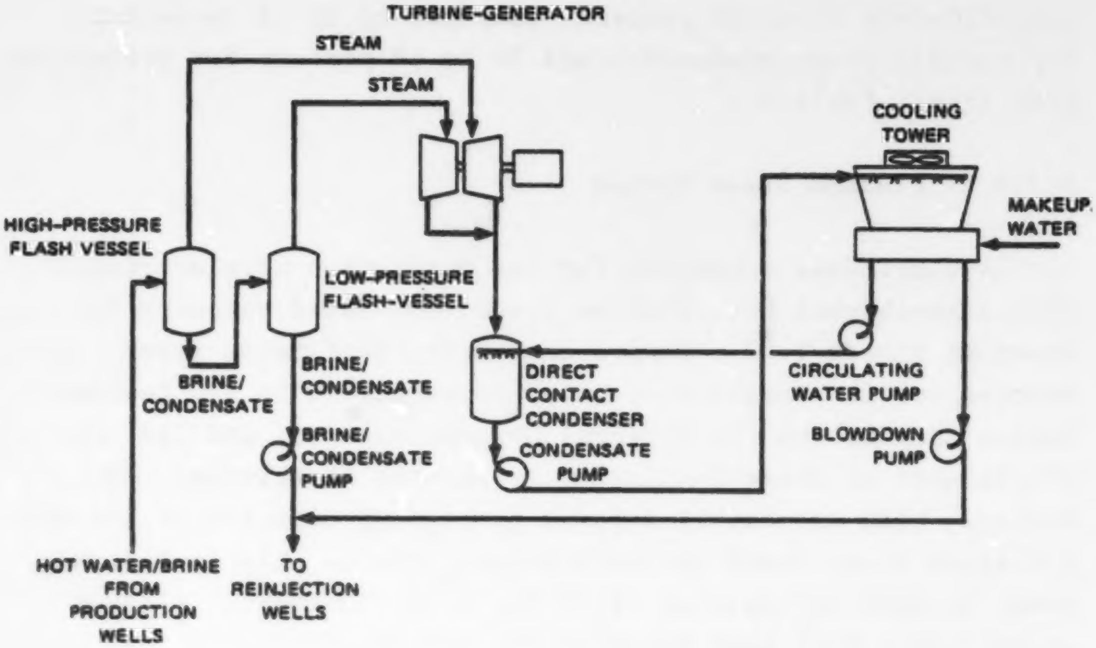
TURBINE-GENERATOR
STEAM
STEAM
COOLING TOWER
MAKEUP WATER
HIGH-PRESSURE FLASH VESSEL
LOW-PRESSURE FLASH-VESSEL
BRINE/ CONDENSATE
BRINE/ CONDENSATE
DIRECT CONTACT CONDENSER
CIRCULATING WATER PUMP
BRINE/ CONDENSATE PUMP
CONDENSATE PUMP
BLOWDOWN PUMP
HOT WATER/BRINE FROM PRODUCTION WELLS
TO REINJECTION WELLS

Figure 8-10. Simplified Schematic of a Two-Stage Flashed Steam Energy Conversion System

Source: Ramachandran, G. et al. Economic Analyses of Geothermal Energy Development in California, 2 Vols. Stanford Research Institute. Prepared for U.S. Energy Research and Development Administration and California Energy Resources Conservation and Development Commission. Contract No. ERDA/SAN E(04-3)-115-P.A.108. May 1977. p. 32.

fluid may issue at the surface as a two-phase mixture of steam and hot water (or brine). Additional quantities of steam are produced in a separator by flashing the fluid at a reduced pressure and separating the two phases. After the removal of particulates, the steam is expanded in a conventional low-pressure steam turbine which then powers a generator to produce electricity. The remainder of the power cycle is similar to the previously discussed cycle for producing electricity from dry steam.[1]

It is usually desirable to flash the residual liquid a second time, using the secondary steam in lower stages of a turbine. This process option is demonstrated in the flashed steam system illustrated in Figure 8-10. Theoretically, energy extraction is maximized by flashing the residual fluid an infinite number of times. However, more than two flash stages appear to be impractical.[2]

For fluids high in dissolved solids or noncondensable gases, flashed steam plants may be impractical. Flashing can result in the deposition of solids, while the presence of noncondensables reduces the net power production from steam turbines.[3] Carryover of salts into the steam can cause corrosion, erosion, or scaling of turbine components.[1] A flashed steam plant may also be unattractive for power production from intermediate-temperature geothermal fluids. The steam yield from such fluids is low, and the consequent increase in production well costs may be prohibitive.[2]

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[1] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, pp. 33-34.

[2] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976, p. 20.

[3] Bloomster, C. H. and C. A. Knutsen. The Economics of Geothermal Electricity Generation from Hydrothermal Resources. Battelle Pacific Northwest Laboratories. BNWL-1989. Richland, Washington: 1976, pp. 33-34.

8.7.1.3 Binary Cycle System

A schematic of a simple binary cycle system is reproduced in Figure 8-11. Only two binary cycle geothermal power plants are in use anywhere in the world: pilot plants of 3.8 MW_e and 0.75 MW_e are operating in Japan and the Soviet Union respectively. Power from the Soviet plant is produced by energy extracted from an 80°C geothermal fluid.[3;4]

San Diego Gas and Electric Company plans to build a 45 MW_e (net) binary cycle demonstration plant at Heber, California. Plant start-up is expected in 1980. The Heber demonstration will have some applicability to roughly 80 percent of the identified liquid-dominated resources in the United States.[5]

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[1] Austin, A. L. and A. W. Lundberg. "Electric Power Generation from Geothermal Hot Water Deposits." Mechanical Engineering 97(12): 18-25, December 1975.

[2] Sacarto, D. M. State Policies for Geothermal Development NSF/RA-760230. Funded through grant by National Science Foundation. Denver, Colorado: National Conference of State Legislatures, 1976, p. 27.

[3] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 18.

[4] Austin, A. L. and A. W. Lundberg, *op.cit.*

[5] Lombard, G. L. "Heber Geothermal Demonstration Plant." Geothermal Resources Council, Transactions. Vol. 1, May 1977, pp. 195-196.

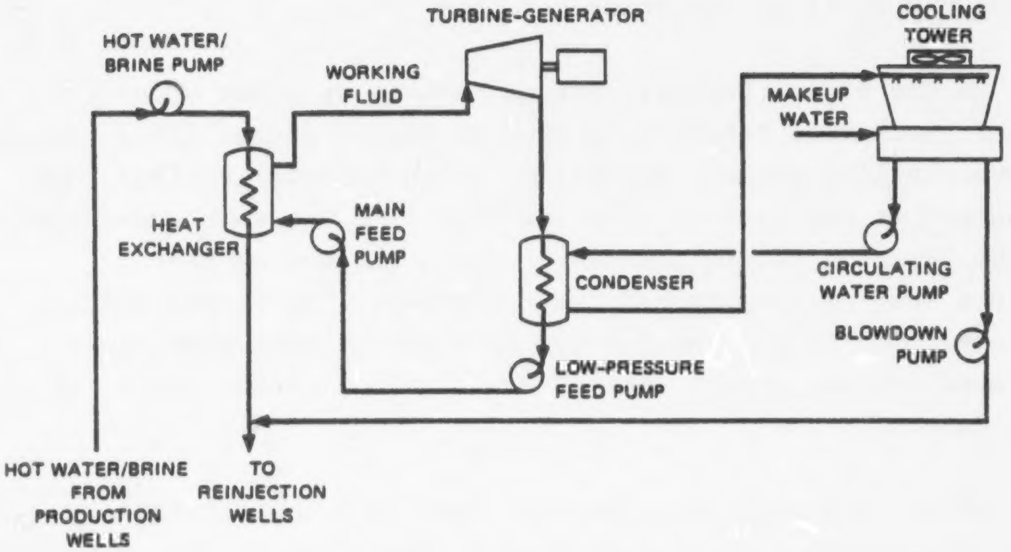
TURBINE-GENERATOR
COOLING TOWER
HOT WATER/ BRINE PUMP
WORKING FLUID
MAKEUP WATER
HEAT EXCHANGER
MAIN FEED PUMP
CONDENSER
CIRCULATING WATER PUMP
BLOWDOWN PUMP
LOW-PRESSURE FEED PUMP
HOT WATER/BRINE FROM PRODUCTION WELLS
TO REINJECTION WELLS

Figure 8-11. A Schematic Diagram of a Binary Cycle Energy Conversion System

Source: Ramachandran, G. et al. Economic Analyses of Geothermal Energy Development in California 2 Vols. Stanford Research Institute. Prepared for U.S. Energy Research and Development Administration and California Energy Resources Conservation and Development Commission. Contract No. ERDA/SAN E(04-3)-115-P.A.108. May 1977. p. 33.

Magma Power Company is constructing an 11.2 MW_e (net) "dual binary cycle" power plant at East Mesa in Imperial Valley, California. Heat is recovered from a high-temperature geothermal fluid by two binary cycle systems. Magma anticipates start-up of the new plant in the spring of 1978.[1]

In the binary process, thermal energy in a hot water (or brine) geothermal resource is used to heat a second fluid having a lower boiling point. Typically, a conventional surface heat exchanger is employed to transfer heat from the geothermal fluid to the "working" fluid. More recently, the use of direct contact heat exchangers has been proposed. The direct contact exchanger may reduce the buildup of scale on heat exchanger surfaces and may reduce capital costs. Total power costs may be similar.[2,3,4]

After heat exchange, the vaporized "working" fluid is expanded through a turbine to produce electricity. The expanded fluid is then condensed and pumped up to its initial pressure for recycle through the system.[5]

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[1] Hinrichs, T. C. and H. W. Falk, Jr. "The East Mesa 'Megamax Process' Power Generation Plant." Geothermal Resources Council, Transactions. Vol. 1, May 1977, pp. 141-142.

[2] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976. p. 15.

[3] Sheinbaum, I. "Power Production from High Temperature Geothermal Waters." Geothermal Energy Magazine 4(10): 17-24, October 1976.

[4] Harris, J. S., et al. "Conceptual Design and Evaluation of Geothermal-Driven 50 MWe Power Plants." Geothermal Resources Council, Transactions. Vol. 1, May 1977, pp. 195-196.

[5] The Ben Holt Company and Procon, Inc., *op.cit.*, p. 25.

Light aliphatic hydrocarbons (such as propane, isobutane and isopentane) appear to be the best candidate working fluids for most binary cycles using a surface heat exchanger. The freons may also be used. Other suggested working fluids are ammonia, sulfur dioxide, carbon dioxide, and light aliphatic olefins. None appear to offer advantages over the light aliphatic hydrocarbons.[1]

The geothermal fluid supplied to a binary cycle power plant may be available as a one-phase brine or as a two-phase mixture of brine and steam. It is usually more desirable to supply the fluid as a one-phase brine; the one-phase brine entails fewer scaling problems[2] and provides more efficient heat exchange. The brine may be maintained as a one-phase fluid by downhole pumps. (These downhole pumps are relatively underdeveloped.)

The binary cycle system has several attractive features compared to flashed steam systems. First, the binary cycle system is potentially more efficient in recovering heat from geothermal fluids whose temperatures are less than 400°F at the wellhead.[3] Second, the binary cycle avoids some of the scaling problems associated with the flashing of geothermal brines.[4]

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[1] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976, p. 26.

[2] Cortez, D. H., Ben Holt, and A. J. L. Hutchinson. "Advanced Binary Cycles for Geothermal Power Production." Energy Sources. Vol. 1, No. 1, 1973. pp. 81, 92.

[3] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 34.

[4] Cortez, D. H., Ben Holt, and A. J. L. Hutchinson, *op.cit.*, pp. 80, 86.

Finally, the power production of binary cycle systems is not impaired by noncondensable gases contained in the geothermal fluid.[1]

8.7.1.4 Hybrid Flashed Steam/Binary Cycle System

Hybrid systems employ elements of both flashed steam and binary cycle technologies. Since May 1976, San Diego Gas and Electric has been operating a "geothermal loop experimental facility" employing one hybrid cycle scheme. The experimental facility is sized to produce 10 MW_e electric power using a hybrid cycle; initial operating experience has been obtained without a turbine/generator installation.[2]

The experimental facility is located at Niland, California, and uses the high-temperature high-salinity brine resource of the Salton Sea Geothermal Anomaly. The primary design and functional intent of the hybrid cycle is to minimize scaling in the brine/working fluid heat exchangers. The hybrid cycle at the Niland test facility consists of: flashing the brine at four successively lower pressures, scrubbing particulates from the flashed steam, and vaporizing the working fluid by condensing the flashed steam in surface heat exchangers. The vaporized working fluid can then be expanded through a turbine to generate electricity. Major problems experienced to date have been scale deposition and injection well plugging. The brine piping network must be continuously cleaned of scale. Continuous operation is limited by scale accumulation at the reinjection pumps.[1,2]

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[1] Bloomster, C. H. and C. A. Knutsen. The Economics of Geothermal Electricity Generation from Hydrothermal Resources. Battelle Pacific Northwest Laboratories. BNWL-1989. Richland, Washington, 1976, p. 34.

[2] Jacobson, W. O. "Recent Operational Experience at the SDG&E/ERDA Niland Geothermal Loop Experimental Facility." Geothermal Resources Council, Transactions, Vol. 1, May 1977, pp. 153-155.

An alternate hybrid cycle has been described by Holt/Procon.[3] In this hybrid process, part of the geothermal brine is flashed into steam. The flashed steam is then used to drive a conventional steam turbine. The residual heat in the brine is then transferred to a working fluid. The vaporized working fluid is used to drive a second turbine. This process appears to be especially susceptible to scaling problems in the brine/working fluid heat exchanger.

8.7.1.5 Total Flow System

Several novel heat engines have been proposed for directly converting the thermal and kinetic energy of a two-phase geothermal fluid into shaft work without phase separation. Energy is recovered by the two-phase expansion of the geothermal fluid. Classes of expanders developed for total flow applications are shown in Table 8-47. Operating characteristics and descriptions of total flow expanders are often proprietary.[4,5]

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[1] Jacobson, W. O. "Recent Operational Experience at the SDG&E/ERDA Niland Geothermal Loop Experimental Facility." Geothermal Resources Council, Transactions, Vol. 1, May 1977, pp. 153-155.

[2] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976, p. 15.

[3] *Ibid.*

[4] Austin, A. L. and A. W. Lundberg. "Electric Power Generation from Geothermal Hot Water Deposits." Mechanical Engineering 97(12): 18-25, December 1975.

[5] The Futures Group. A Technology Assessment of Geothermal Energy Resource Development. Prepared for National Science Foundation, Contract No. C-836. Glastonbury, Connecticut: The Futures Group, April 15, 1975, p. 34.

TABLE 8-47. CLASSES OF EXPANDERS DEVELOPED OR CONSIDERED FOR TOTAL FLOW APPLICATIONS

Class	Examples
Impulse/reaction machines	
Axial flow	Curtis/Rateau steam turbine
Radial inflow	Francis turbine
Radial outflow	Hero's turbine
	Bladeless impuse or reaction drag turbine
Positive displacement machines	Helical screw expander
	Rotating oscillating vane machine
Impulse machines	
Tangential flow	Pelton wheel
	Re-entry turbine
Axial flow	DeLaval turbine
	Curtis turbine

Source: Austin, A. L. and A. W. Lundberg. "Electric Power Generation from Geothermal Hot Water Deposits." Mechanical Engineering 97(12): 18-25, December 1975.

One proposed design uses a helical screw which rotates as the fluid expands along its axis.[1] Other designs employ principles applied in waterwheels. While total flow expanders theoretically recover more energy than other systems, little operating experience has been attained. Potential problems are associated with scaling, corrosion, and erosion of metal parts.[2]

8.7.2 Input Requirements

Input requirements and outputs of electric power generation are associated with the electric power plant and the reinjection well piping network. Manpower, materials and equipment, finances, water, land, and ancillary energy requirements for electric power generation and reinjection of spent geothermal fluids are discussed in the following sections.

8.7.2.1 Manpower

Manpower requirements for the construction, operation, and maintenance of a reinjection well piping network and geothermal power plant have been estimated by Bechtel Corporation for the Federal Energy Administration. Bechtel's estimates of construction manpower include manpower requirements during the design, procurement, construction, testing, and start-up of the power plant and piping network. Construction manpower for the reinjection well piping network previously defined in Section 8.4.2 is reported in Table 48. Estimates reported herein are simply extrapolated from those reported by Bechtel.

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[1] Austin, A. L. "Total Flow Concept for Geothermal." Proceedings of the Conference on Research for the Development of Geothermal Energy Resources. NSF-RA-N-74-159. Organized by Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, September 23-25, 1974, pp. 186-194.

[2] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976, p. 15.

[3] Federal Energy Administration, Interagency Task Force on Geothermal Energy. Project Independence Blueprint, Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974, pp. D-3 to D-7.

Construction manpower for the geothermal power plant are reported in Table 8-49. Manpower requirements for the construction of a hot water or brine power plant are assumed to be 40 percent greater than the manpower requirements for construction of a dry-steam plant.[1] Manpower requirements for construction of a power plant using a fluid from a hot rock system are probably similar to the manpower requirements for a brine power plant.

Personnel required for the operation and maintenance of the reinjection piping network are summarized in Table 8-50. Estimates of the personnel required to operate and maintain a 100 MW_e dry-steam power plant are presented in Table 8-51. Manpower estimates for the operation and maintenance of a 100 MW_e brine power plant are presented in Table 8-52, as estimated by Holt/Procon.[2,3]

8.7.2.2 Materials and Equipment

Construction of the reinjection piping network and power plant requires heavy equipment to: transport and handle pipe,

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[1] Federal Energy Administration, Interagency Task Force on Geothermal Energy. Project Independence Blueprint, Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974, p. D-3.

[2] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976, p. 102.

[3] Data reported by Holt/Procon describe a 50 MWe plant; data for a 100 MWe plant are assumed to be double those of 50 MWe plant.

TABLE 8-48. MANPOWER REQUIRED TO CONSTRUCT A REINJECTION PIPING NETWORK ASSOCIATED WITH A 100 MW_e POWER PLANT

Personnel Description	Manpower, total man-years			
	Hot water resource Binary fluid cycle	Hot water resource Direct steam flashing cycle	Hot rock resource Binary fluid cycle	Steam resource[c] Direct steam cycle
Design				
Mechanical engineer[a]	0.9	1.0	0.1	--
Civil engineer[a]	0.4	0.5	0.1	--
Draftsman[a]	0.4	0.5	0.1	--
Draftsman[a]	0.4	0.5	0.1	--
Route surveyor[a]	1.6	1.8	0.2	--
Construction				
Civil engineer[b]	0.9	1.0	0.1	--
Foreman[b]	1.8	2.0	0.3	--
Pipefitter[b]	3.9	4.2	0.4	--
Welder[b]	2.6	2.8	0.3	--
Carpenter[b]	1.3	1.4	0.2	--
Concrete worker[b]	2.6	2.8	0.3	--
Dozer operator[b]	1.3	1.4	0.2	--
Truck driver[b]	2.6	2.8	0.3	--
Crane operator[b]	1.3	1.4	0.2	--
Insulation installer[b]	0.6	0.7	0.1	--
Inspector (construction)[b]	0.7	0.8	0.1	--
Inspector (nondestructive testing)[b]	0.8	0.9	0.1	--
TOTAL	24	27	3	~1

[a] Based on 4-month design program.

[b] Based on 8-month construction program.

[c] Only one re-injection well required.

Source: Federal Energy Administration. Interagency Task Force on Geothermal Energy. Project Independence Blueprint Final Task Force Report: Geothermal Energy. Washington, D.C. U.S. Government Printing Office. 1974. p. D-6.

TABLE 8-49. MANPOWER REQUIRED TO CONSTRUCT A 100 MW_e GEOTHERMAL POWER PLANT[a]

Personnel Description	Manpower, man-years					
	Hot water resource			Dry steam resource		
	1st yr.	2nd yr.	3rd yr.	1st yr.	2nd yr.	3rd yr.
Structural Engineer	1.4	0.7	-	1.0	0.5	-
Mechanical Engineer	3.5	1.8	-	2.5	1.3	-
Civil Engineer	1.4	0.7	-	1.0	0.5	-
Electrical Engineer	2.1	1.1	-	1.5	0.8	-
Corrosion Engineer	0.2	-	-	0.1	-	-
Architect	0.4	0.1	-	0.3	0.1	-
Draftsman (Designer Quality)	2.8	1.4	-	2.0	1.0	-
Draftsman	8.1	2.8	-	5.8	2.0	-
Topographical Surveyor	2.3	-	-	1.7	-	-
Purchasing Agent	0.4	0.4	-	0.3	0.3	-
Equipment Inspector	0.7	0.7	-	0.5	0.5	-
Corrosion Engineer	0.1	-	0.1	0.1	-	0.1
Civil Engineer (Construction)	1.4	1.4	1.4	1.0	1.0	1.0
Mechanical Engineer	0.7	0.7	0.7	0.5	0.5	0.5
Electrical Engineer	1.4	1.4	1.4	1.0	1.0	1.0
Surveyor (Construction Control)	2.8	2.8	0.7	2.0	2.0	0.5
Inspector (Construction)	2.1	2.1	2.1	1.5	1.5	1.5
Superintendent	0.7	0.7	0.7	0.5	0.5	0.5
Asst. Superintendent (Contruction)	0.7	0.7	0.7	0.5	0.5	0.5
Foreman	3.5	4.2	3.5	2.5	3.0	2.5
Electrician	2.8	4.2	4.2	2.0	3.0	3.0
Pipe Fitter	-	-	7.0	-	-	5.0
Welder	2.8	5.6	4.2	2.0	4.0	3.0
Millwright	-	4.2	2.8	-	3.0	2.0
Iron-Worker	2.1	4.2	2.8	1.5	3.0	2.0
Concrete Worker	1.1	1.1	4.9	0.7	0.7	3.5
Sheetmetal Worker	-	2.1	4.2	-	1.5	3.0
Carpenter	7.0	7.0	2.8	5.0	5.0	2.0
Plumber	-	-	2.8	-	-	2.0
Insulation Installer	-	1.4	2.8	-	1.0	2.0
Tile-Setter	-	-	1.1	-	-	0.7
Painter	-	2.1	2.8	-	1.5	2.0
Instrument Technician	-	1.1	2.1	-	0.7	1.5
Machinist	-	1.4	1.4	-	1.0	1.0
Rigger	1.1	2.8	2.1	0.7	2.0	1.5
Truck Driver	3.5	3.5	2.8	2.5	2.5	2.0
Crane Operator	2.1	2.8	2.1	1.5	2.0	1.5
Timekeeper	1.1	1.1	1.1	0.5	0.5	0.5
Warehouseman	1.1	2.1	1.4	0.5	1.5	1.0
Pile-Driver	2.8	-	-	2.0	-	-
Laborer	10.5	14.0	7.0	7.5	10.0	5.0
TOTAL	75	84	74	53	60	52

[a] Based on 1.5 year design schedule, 3 year construction schedule.

Source: Federal Energy Administration, Interagency Task Force on Geothermal Energy. Project Independence Blueprint, Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office, 1974. p. D-6.

TABLE 8-50. MANPOWER REQUIRED TO OPERATE AND MAINTAIN A RE-INJECTION PIPING NETWORK ASSOCIATED WITH A 100 MW_e POWER PLANT

Personnel Description	Manpower, average man-years per year Hot water resource Binary fluid cycle	Hot water resource Direct steam flashing cycle	Hot rock resource Binary fluid cycle	Steam resource Direct steam cycle
Operation				
Field Operator	1.3	1.4	0.2	-
Routine Maintenance				
Foreman	0.1	0.1	~ 0	-
Pipefitter	0.3	0.3	~ 0	-
Welder	0.1	0.1	~ 0	-
Insulation Installer	0.3	0.3	~ 0	-
Crane Operator	0.1	0.1	~ 0	-
TOTAL	2.2	2.3	0.3	~ 0.1

Source: Federal Energy Administration. Interagency Task Force on Geothermal Energy. Project Indepenpendence Blueprint Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office. 1974. p. D-7.

TABLE 8-51. MANPOWER REQUIRED TO OPERATE AND MAINTAIN A 100 MW$_e$ GEOTHERMAL STEAM POWER PLANT

Personnel Description	Manpower, average man-years per year
Operation	
Plant superintendent	0.5
Shift foreman	1.5
Plant operator	4.5
Routine Maintenance	
Mechanical engineer (turbine specialist)	0.1
Corrosion engineer	
Instrument technician	0.3
Foreman	0.1
Millwright	0.1
Machinist	0.1
Pipefitter	0.1
Welder	0.1
Electrician	0.1
Insulation installer	0.1
Painter	0.1
Rigger	0.1
Crane Operator	
Laborer	0.1
TOTAL	8

Source: Federal Energy Administration. Interagency Task Force on Geothermal Energy. Project Independence Blueprint Final Task Force Report: Geothermal Energy. Washington, D.C.: U.S. Government Printing Office. 1974. p. D-7.

TABLE 8-52. MANPOWER REQUIRED TO OPERATE AND MAINTAIN A 100 MW$_e$ HOT WATER OR BRINE POWER PLANT

Personnel Description	Required Number of Personnel
Superintendent	1
Office manager	1
Electrician	4
Instrument specialist	
Mechanic	
Laborer	2
Operator	18
TOTAL	26

Source: The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976. p.102.

prepare pipeline corridors, prepare the site of the power plant, prepare transmission line corridors, install power plant equipment, and construct related surface facilities. None of this equipment is permanently committed to the reinjection piping network and power plant.

Steel in the piping network is the largest material requirement of the reinjection system. Based on the previous discussion in Section 8.6.2.2, steel used in the reinjection piping network is estimated as the following:

Hot water resource	2200-2400 tons
Hot rock resource	360 tons
Steam resource[1]	40 tons.

Major equipment installed in geothermal power plants include: heat exchangers, turbine-generators and electrical gear, pumps, cooling tower, flash drums, accumulators, and scrubbers.

8.7.2.3 Economics

Milora and Tester[2] have developed capital costs estimates for binary cycle and flashed steam cycle power plants utilizing a 150°C geothermal fluid. Capital costs have also been developed for a binary cycle power plant utilizing a 250°C geothermal fluid produced from a hot rock geothermal development. These costs estimates are presented in Table 8-53, and are among the most recent available. Capital costs for the reinjection

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[1] Only one reinjection well is required.

[2] Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: The MIT Press, 1976, pp. 105-106.

TABLE 8-53. ESTIMATED CAPITAL COSTS OF POWER PLANT (AND ASSOCIATED REINJECTION PIPING NETWORK) PRODUCING 100 MW_e ELECTRIC POWER[a]

Cost Component	Geothermal Resource Development Hot water @150°C Binary-fluid cycle	 Hot water @150°C Flashed steam cycle	 Hot rock: water @250°C Binary-fluid cycle
Power plant			
Turbine	$ 308,000	$41,700,000	$ 205,000
Generator	1,130,000	1,130,000	1,130,000
Pumps	740,000	250,000	255,000
Turbine drive	87,600		10,000
Heat exchanger	11,000,000	-	3,840,000
Flashing tanks and cyclones	-	200,000	-
Condenser/desuperheater	7,280,000	500,000	8,770,000
Total purchased equipment	20,500,000	43,800,000	14,200,000
Total power plant capital investment	$56,800,000 $568/$kw_e$	$121,000,000 $1,210/$kw_e$	$39,400,000 $394/$kw_e$
Reinjection piping network	$ 9,600,000	$10,400,000	$ 1,500,000

[a] 1976 Dollars

Source: Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: the MIT Press, 1976.

piping network have been estimated by the method outlined in Section 8.5.2.3; these costs are also summarized in Table 8-53. The costs for the hot water power plants confirm trends reported by Holt/Procon:[1] binary cycle systems are more efficient and economic than flashed steam systems at lower fluid temperatures. Lower capital costs per kilowatt generating capacity are expected for the flashed steam cycle at higher geothermal fluid temperatures.

Total capital and annual costs for the production of electricity from hot brines and hot rock are summarized in Table 8-54. These cost estimates are subject to change as the technologies are further developed and ultimately demonstrated. Costs for the production of electricity from three low salinity, water-dominated resources are reported in Table 8-55, as estimated by Bloomster and Knutsen.[2] Data in Table 8-55 illustrate the economies resulting from the increased efficiency of energy extraction at higher temperatures. At high temperatures, the flashed steam cycle is more economic than the binary cycle.

Capital costs for new power generation units at The Geysers dry steam field amount to about $170/kw (in 1976 dollars).[3]

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[1] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976.

[2] Bloomster, C. H. and C. A. Knutsen. The Economics of Geothermal Electricity Generation from Hydrothermal Resources. Battelle Pacific Northwest Laboratories. BNWL-1989. Richland, Washington, 1976. Tables 2, 7.

[3] Greider, B. "Status of Economics and Financing of Geothermal Energy Power Production." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 2305-2314.

TABLE 8-54. COST SUMMARY FOR THE PRODUCTION OF ELECTRICITY FROM 100 MW_e HOT WATER POWER PLANTS[a]

	Geothermal Resources Development		
Cost Components	Hot water @150°C Binary-fluid cycle	Hot water @150°C Flashed steam cycle	Hot rock: water @250°C Binary-fluid cycle
Capital Costs			
Exploration[b]	$ 7,200,000	$ 7,200,000	$ 7,200,000
Wells[c]	43,300,000	47,300,000	13,000,000
Well-head production system[d]	12,000,000	13,000,000	1,800,000
Power plant[e]	56,800,000	121,000,000	39,400,000
Reinjection piping network[e]	9,600,000	10,400,000	1,500,000
TOTAL	$129,000,000	$199,000,000	$62,900,000
Annual Costs			
Fixed charges[f]	$ 21,900,000	$ 33,800,000	$10,700,000
Operating and maintenance[g]	1,000,000	1,000,000	1,000,000
Power generating cost at busbar[h]	3.1¢/kwh	4.7¢/kwh	1.6¢/kwh

[a] Costs in 1976 dollars.

[b] Scaled from data in Table 8-14 and escalated to 1976.

[c] From Table 8-25.

[d] From Table 8-44.

[e] From Table 8-53.

[f] @17% per year.

[g] From Milora and Tester.

[h] Based on load factor of 85%; plant operates 7,446 hr/year.

Source: Milora, S. L. and J. W. Tester. Geothermal Energy as a Source of Electric Power: Thermodynamic and Economic Design Criteria. Cambridge, Massachusetts: the MIT Press, 1976.

TABLE 8-55. COSTS FOR ELECTRICITY GENERATED FROM THREE REPRESENTATIVE HOT WATER RESERVOIRS[a]

Development Technology	Wellhead Temperature, °C	Powerplant size, MWe		Powerplant Capital Cost	Total Cost of Generating Electricity
		Gross	Net		
1. Two stage flashed steam	250	55	53.0	$291/kw	1.7¢/kwh
2. Binary cycle	250	55	46.1	$329/kw	2.0¢/kwh
3. Binary cycle	200	55	44.5	$335/kw	2.8¢/kwh
4. Binary cycle	150	55	45.9	$375/kw	8.5¢/kwh

[a] 1976 conditions.

Source: Greider, R. "Economic Considerations for Geothermal Exploration in the Western United States," Bulletin, Geothermal Resources Council, Davis, California, May/June 1974. Tables 2, 7.

Stanford Research Institute has estimated that the total capital investment at a dry steam field ranges from $200-280 per kilowatt of capacity. The busbar price of electricity from a dry steam power plant has been reported as 2¢/kwh.[1]

8.7.2.4 Water

By far the largest use of water at a geothermal power plant is cooling. This requirement varies with the power production method, the cooling method, and the potential requirement[2] for reinjection of a volume of fluid equal to the volume of the extracted fluid.

Anglin[3] has estimated the cooling water requirements for 50 MWe geothermal brine power plants located at Heber, California. These data are summarized below, as scaled to a facility size of 100 MWe:

	Water Evaporated	Blowdown	Total Make-up
		acre-ft/year	
One-stage flashed steam	10,300	3,400	13,700
Two-stage flashed steam	9,500	3,200	12,700
Binary cycle	10,000	3,300	13,300

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[1] Romachandran, G., et al. Economic Analyses of Geothermal Energy Development in California, 2 Vols. Stanford Research Institute. Prepared for U.S. Energy Research and Development Administration and California Energy Resources Conservation and Development Commission. Contract No. ERDA/SAN E(04-3)-115-P.A. 108. May 1977. pp. 74-75.

[2] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976, p. 22.

[3] *Ibid.*

Similar cooling water requirements are expected for systems using a geothermal fluid produced in a hot rock development. The above tabulated data describe the typical use of wet-cooling towers.

As discussed earlier, condensed turbine exhaust from dry steam and flashed steam systems can completely satisfy make-up requirements for cooling water. The above make-up requirements for flashed steam systems exist only when complete reinjection of the geothermal fluid is required.

8.7.2.5 Land

From discussions with drillers, Anglin[1] has concluded that about one-half acre per reinjection well is permanently committed to the geothermal fluid reinjection network. Included in the above estimate are land areas required for the piping network, service roads, pumps, and the like. Anglin has also estimated land requirements for power generation and transmission facilities to be 8 MW_e/acre for a flashed steam plant and 11 MW_e/acre for a binary plant. At The Geysers, land requirements have been reported as 27.5 MW_e/acre.[2] Based on the above estimates and the required number of reinjection wells for a 100 MW_e complex, the following areas are assumed to be permanently committed to power production facilities and the reinjection piping network:

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[1] Anglin, R. L. Potential Power Generation Utilizing the Geothermal Resource at Heber, Imperial County, California: Water and Land Use Issues. Working Paper No. 2, Jet Propulsion Laboratory, California Institute of Technology, December 14, 1976.

[2] The topography of the region severely constrains plant layout design at The Geysers.

Hot water resource	31-37 acres
Hot rock resource	15 acres
Steam resource	4 acres

8.7.2.6 Ancillary Energy

Holt/Procon[1] has indicated that about 5-20 percent of the gross output from brine power plants is required for plant use, including the pumping of geothermal brine. This is energy supplied from inside the plant boundaries and strictly defined is not ancillary energy. Hence, the geothermal power generation facilities have no ancillary energy requirements.

8.7.3 Outputs

Outputs associated with the generation of electricity from geothermal resources are discussed in the following sections. These outputs include: air emissions, water effluents, solid wastes, noise pollution, occupational health and safety hazards, and odors.

8.7.3.1 Air Emissions

Air emissions from geothermal power generation are chiefly emissions of noncondensable gases from gas ejectors, and noncondensable gases and particulates from cooling towers (if direct contact condensers are used). Only emissions from The Geysers have been quantified; likely emissions from brine power plants are discussed qualitatively. Data on emissions from brine plants will not be available until brine plants are built in the U.S.

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[1] The Ben Holt Company and Procon, Inc. Energy Conversion and Economics for Geothermal Power Generation at Heber, California, Valles Caldera, New Mexico, and Raft River, Idaho - Case Studies. Prepared for Electric Power Research Institute, EPRI ER-301, Research Project 580, Topical Report 2, November 1976.

Currently, power generating units at The Geysers emit air pollutants from two sources: gas ejectors and cooling towers. Estimates of the uncontrolled release of pollutants from these sources are shown in Table 8-56, as measured by Pacific Gas and Electric Company.[1]

About 96 percent of the nitrogen and essentially all of the oxygen present in the ejector off-gas originate from air dissolved into the cooling waters in the cooling towers, and air that leaks into the subatmospheric pressure portions of the power generating equipment. Trace amounts of radon are also present in the ejector off-gas.[2] The other gases were part of the geothermal fluids.

Two other groups of elements have been detected in trace amounts. One of these groups includes certain elements normally found in soil. This group includes silicon, aluminum, iron, calcium, sodium, magnesium, titantium, and strontium, which are emitted in the cooling tower drift in quantities less than one lb/day each. The other group of elements includes lead, copper, chromium, manganese, nickel, and zinc. These five metals may originate from the rock in the steam field or may be eroded from the piping and valves of the steam transportation network. These elements are emitted in the cooling tower drift in quantities less than 0.2 lb/day each.[3]

Pollution control strategies are primarily designed to control hydrogen sulfide emissions. The current abatement program at The Geysers includes plans to install a ducting system on

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[1] Griffin, D. P., Jr., H. K. McCluer, and R. O. Dean. "Emissions of Noncondensible Gases and Solid Materials from the Power Generating Units at The Geysers Power Plant." Report 7485.16-74. Pacific Gas and Electric Company, Department of Engineering Research. July 30, 1974. 13 pp.

[2] *Ibid.*

[3] *Ibid.*

TABLE 8-56. UNCONTROLLED EMISSIONS OF NONCONDENSABLE GASES AND SOLID MATERIALS FROM THE POWER GENERATING UNITS AT THE GEYSERS POWER PLANT[a]

Source	Constituent	Range of Concentrations, by Vol.		Average Concentrations		Mass Flow
		Low	High	by Vol.	by Wt.	
Ejector off-gas	Carbon dioxide	22.6%	63.6%	41.7%	59.9%	5240 lb/hr
	Hydrogens sulfide	0.52%	1.60%	1.08%	1.2%	105 lb/hr
	Methane	2.57%	13.2%	7.2%	3.8%	333 lb/hr
	Oxygen	1.23%	15.4%	8.0%	8.4%	735 lb/hr
	Nitrogen	5.8%	50.1%	28.1%	25.8%	2260 lb/hr
	Hydrogen	8.2%	21.7%	13.9%	0.9%	79 lb/hr
Cooling tower exhaust	Hydrogen sulfide	--	--	5.1 ppm	--	275 lb/hr
	Ammonia	--	--	12.2 ppm	--	332 lb/hr
	Carbon dioxide	--	--	5.06 ppm	--	254 lb/hr
Cooling tower drift[b]	Arsenic	--	--	--	.059 ppm	.0096 lb/d
	Boron	--	--	--	129 ppm	21 lb/d
	Mercury	--	--	--	.0037 ppm	.00060 lb/d

[a] Scaled to basis of 100 MW_e generating capacity.

[b] Drift rate of .15 percent by weight of the cooling water flowing through tower, equal to 162,000 lb/d.

Source: Griffin, D. P., Jr., H. K. McCluer, and R. O. Dean. "Emissions of Noncondensable Gases and Solid Materials from the Power Generating Units at the Geysers Power Plant." Report 7485.16-74. Pacific Gas and Electric Company, Department of Engineering Research. July 30, 1974. 13 pp.

existing units to transfer the gases from the gas ejectors to the cooling towers. The noncondensable gases routed from the gas ejector are essentially "scrubbed" by cooling water in the cooling tower. An iron catalyst added to the cooling water promotes the oxidation of hydrogen sulfide to elemental sulfur. The sulfur sludge is removed in settling ponds and conveyed to a disposal site. Overall H_2S abatement levels in excess of 90 percent have been reported.[1]

Future generating units will use an alternate control technique. In the proposed new units, surface condensers will be substituted for direct contact condensers: the exhaust steam will no longer be directly contacted with cooling water. Up to 90 percent of the H_2S in the condensing steam will be released by the off-gas ejectors. The off-gas will be conveyed to a Stretford unit, where H_2S will be oxidized to elemental sulfur. The sulfur sludge produced by the Stretford will probably be conveyed to a disposal site. About 10 percent of the H_2S in the condensing steam will remain in the steam condensate. In current designs, this condensate will be added to the circulating cooling water. The H_2S in the cooling water will be stripped at the cooling tower and emitted to the atmosphere. The amount of H_2S emitted at the cooling tower can be reduced by treatment of the condensate from surface condensers with H_2O_2 or O_3. This treatment and the use of a Stretford for treatment of the ejector off-gas remove about 99 percent of the H_2S in the inlet steam stream.[1,2]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 79.

Other processes are being developed to remove H_2S from geothermal steam upstream of the power plant. The presence of ammonia and carbon dioxide complicates the selection of absorption liquors for the removal of H_2S. The EIC Corporation is developing a scrubbing system using a solution of a metal salt, such as $CuSO_4$, to convert the H_2S to various copper sulfide precipitates. $CuSO_4$ is regenerated on-site by oxygen pressure leaching. Removals in excess of 90 percent have been routinely achieved. Full scale testing on a steam flow of about 100,000 lb/hr is being considered.[3,4] Another scrubbing process is being developed by Republic Geothermal, Inc. and FMC Corporation. The Republic/FMC process uses an aqueous hydrogen peroxide and sodium hydroxide solution to oxidize the H_2S to various sulfates and elemental sulfur. Removal efficiencies of up to 96 percent have been obtained in pilot tests.[5] The Republic/FMC process is intended mostly for control of emissions during drilling.

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 80.

[2] Ramachandran, G., et al. Economic Analyses of Geothermal Energy Development in California, 2 Vols. Stanford Research Institute. Prepared for U.S. Energy Research and Development Administration and California Energy Resources Conservation and Development Commission. Contract No. ERDA/SAN E(04-3)-115-P.A. 108. May 1977. p. 41.

[3] Harvey, W. W. and F. C. Brown. "The $CuSO_4$ Process for Removal of H_2S from Geothermal Steam." Geothermal Resources Council, Transactions. Vol. 1, May 1977, pp. 135-136.

[4] Tomany, J. P. "Air Pollution Control Plans for Geothermal Energy Plants." Geothermal Resources Council, Transactions. Vol. 1, May 1977, pp. 295-296.

[5] *Ibid.*

As previously discussed in Section 8.5.3.1, estimates of emissions from the development of liquid-dominated systems can be prepared only from a detailed site-specific analysis of the chemistry of the geothermal fluid.[1]

In flashed-steam systems, essentially all of the noncondensables present in the geothermal fluids are vented to the atmosphere. Control techniques similar to those developed at The Geysers should be applicable.[2] If reinjection of condensed steam and residual brine is required, the only emission sources are off-gas ejectors unless condensed steam is used as cooling water make-up.

In binary power plants, if the geothermal fluid is maintained at reservoir pressure, no noncondensable gases are emitted: the gases are maintained in solution in the brine.[3] If the geothermal fluid issues as a two-phase mixture, noncondensables are separated from the liquid at the binary heat exchanger, and subsequently released to the atmosphere.

Potential air emissions from hot rock resource developments have not been discussed quantitatively or qualitatively. Essentially no noncondensable gases have been detected during initial operation of the demonstration facility at Fenton Hill, New Mexico.[4]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 74.

[2] *Ibid.*

[3] *Ibid.*

[4] Private communication with M. C. Smith, December 13, 1977.

Concentrations of noncondensable gases emitted from an uncontrolled vent at the geothermal loop experimental facility in Nilands, California are shown in Table 8-57. Emission rates have not been reported.

TABLE 8-57. CONCENTRATIONS OF VARIOUS CHEMICAL SPECIES IN NONCONDENSABLE EMISSIONS FROM NILAND TEST FACILITY

Species	Concentration (by volume)
H_2S	1500-4900 ppm
CO_2	96-98%
H_2	<0.05-0.34%
N_2	0.2-0.7%
CH_4	0.5-1.4%
C_2H_6	<0.03%

Source: Phelps, P. L. and L. R. Anspaugh, eds. Imperial Valley Environmental Project: Progress Report. UCRL-50044-76-1. Lawrence Livermore Laboratory. Prepared for U.S. Energy Research and Development Administration under Contract No. W-7405-Eng-48. Livermore, CA. p. 40.

8.7.3.2 Water Effluents

The most significant water effluents discharged by a geothermal power plant are cooling tower blowdowns and spent geothermal brines. The ultimate disposal of these wastes is dependent on the chemistry of the effluent, adjacent land uses, and the geothermal plant design. Disposal may be one or a combination of the following practices:

- reinjection,
- discharge to surface waters, or.
- disposal to lined or unlined evaporation or sedimentation ponds.

Reinjection is usually most desirable.[1]

Each 100 MW_e of generating capacity at The Geysers produces about 1100 acre-feet per year of excess steam condensate which is withdrawn from the cooling system as blowdown.[2] Cooling tower blowdowns from flashed-steam and brine power plants have been quantified in Section 8.7.2.4. Total quantities of blowdown and spent brine to be disposed are summarized in Table 8-58. The brine flows are based on the geothermal fluid requirements defined previously in Section 8.5.2. Characteristics of these water effluents are highly site and process specific.

Some potential exists for contamination of ground water if the spent brine and blowdown are disposed by reinjection. However, this potential hazard can be reduced to insignificance by proper and complete casing of the reinjection wells. Rupture of the piping network is rare, but can be a source of contamination of surface water.

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[1] Morrison, R. "Surface Disposal of Geothermal Brines." Geothermal Energy Magazine 5(8): 40-42, August 1977.

[2] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 56.

TABLE 8-58. WATER EFFLUENTS PRODUCED DURING POWER PRODUCTION AT A 100 MW_e POWER PLANT

Geothermal Resource - Conversion Technology	Cooling Water Blowdown acre-feet/year	Spent Brine acre-feet/year
1. Hot Water		
a. Binary fluid cycle[a]	3,200	51,000
b. Flashed steam cycle[b]	3,300-3,400	42,000-43,000[c,d] 52,000[d,e]
2. Hot rock - binary fluid cycle	3,000[f]	17,000[g] 20,000[h]
3. Dry steam - direct steam cycle	1,100	--

[a] Assumes use of surface heat exchangers.

[b] Assumes use of surface or direct contact heat exchangers.

[c] Assumes no legal restriction requiring reinjection and that condensate is not required to dilute residual brine.

[d] Excess steam condensate is classed as spent brine.

[e] Assumes legal restriction requiring complete reinjection of extracted fluids.

[f] Assumes cooling requirement based on hot water conversion technologies.

[g] Assumes that cooling water blowdown can be used as make-up water for hot rock development.

[h] Assumes that cooling water blowdown cannot be used as make-up.

Additional, unquantified water effluents are associated with the operation of hydrogen sulfide removal equipment. The quantities of these wastewaters are certainly less than quantities of spent brine. However, some of these wastes may be highly toxic. Disposal will typically require evaporation or sedimentation ponds or reinjection.

8.7.3.3 Solid Wastes

Solid wastes generated during power production include sludges from hydrogen sulfide removal and solids from scale removal. These solid wastes have not been described quantitatively or qualitatively.

8.7.3.4 Noise Pollution

Noise during power production is chiefly associated with the operation of gas ejectors, cooling towers, and turbine-generators. Typical noise levels for these operations as observed at The Geysers are summarized below:[1,2,3]

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[1] Resource Planning Associates, Inc. Western Energy Resources and the Environment: Geothermal Energy. Prepared for U.S. Environmental Protection Agency, Contract No. 68-01-4100. Washington, D.C.: U.S. Environmental Protection Agency, May 1977, p. 65.

[2] Ecoview Environmental Consultants. Draft Environmental Impact Report for Geothermal Development of Union Oil Company's Leaseholds on the Upper Part of the Squaw Creek Drainage at The Geysers, Sonoma County, California. Napa, California, 1974.

[3] Reed, M. J. and G. E. Campbell. "Environmetal Impact of Development in The Geysers Geothermal Field, U.S.A." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 1399-1410.

Noise Source	Duration	Noise Level	Distance
Jet gas ejector	Continuous		5-10 feet
Unattenuated		117 dBA	
With acoustical insulation		84 dBA	
Cooling tower	Continuous	80-90 dBA	5-10 feet
Turbine-generators building	Continuous	70 dBA	Outside

8.7.3.5 Occupational Health and Safety

Safety hazards associated with the operation and maintenance of a geothermal power plant have not been extensively studied to date. These hazards are similar to those at fossil-fuel plants. Health hazards are chiefly associated with worker exposure to toxic gases, as described in Section 8.5.3.5.

8.7.3.6 Odor

Odors at geothermal developments are chiefly associated with the presence of ammonia and hydrogen sulfide, as described in Section 8.5.3.6. These gases can be emitted in malodorous concentrations via the noncondensable gas vent and the cooling towers.

The inputs and outputs associated with geothermal power plants are summarized in Table 8-59.

8.7.4 Direct Thermal and Other Uses of Geothermal Energy

On a worldwide basis, non-electrical applications of geothermal energy represent an average energy consumption of

TABLE 8-59. SUMMARY OF INPUTS AND OUTPUTS OF A GEOTHERMAL POWER PLANT PRODUCING 100 MW_e

	Hot water/ binary fluid	Hot water/ steam flashing	Hot rock/ binary fluid	Dry steam/ direct use
Input Requirements				
Manpower				
• construction	257 man-years	260 man-years	230 man-years	170 man-years
• operating	28 men	28 men	26 men	8 men
Materials				
• steel in piping network	2200 tons	2400 tons	360 tons	40 tons
Economics				
• capital costs[a]	\$66.4 million	\$131.4 million	\$40.9 million	--
• power generation costs[b]	3.1¢/kwh[c]	4.7¢/kwh[c]	1.6¢/kwh[c]	2.0¢/kwh[d]
Water				
• total make-up	13,000 acre ft/yr[e]	13,000 acre ft/yr[e]	13,000 acre ft/yr[e]	None
Land	31 acres	37 acres	15 acres	4 acres
Ancillary energy	None	None	None	None
Air emissions				
• carbon dioxide	Unknown	Unknown	Unknown	5500 lb/hr
• hydrogen sulfide				380 lb/hr
• methane				330 lb/hr
• hydrogen				80 lb/hr
• ammonia				330 lb/hr
• arsenic				0.01 lb/d
• boron				21 lb/d
• mercury				0.0006 lb/d
Water effluents				
• blowdown	3,000 acre ft/yr	3,000 acre ft/yr	3,000 acre ft/yr	1,100 acre ft/yr
• spent brine	51,000 acre ft/yr	52,000 acre ft/yr	20,000 acre ft/yr	--
Solid wastes	Not quantified	Not quantified	Not quantified	Not quantified
Noise pollution	<90 dB(A)	<90 dB(A)	<90 dB(A)	<90 dB(A)
Occupational health and safety	Not quantified	Not quantified	Not quantified	Not quantified
Odors	NH_3 H_2S	NH_3 H_2S	Unknown	NH_3 H_2S

[a] Based on 150°C resource.

[b] Including capital charges.

[c] 1976 dollars.

[d] 1977 dollars.

[e] Complete reinjection of geothermal fluids.

about 6000 MW_t.[1] While non-electrical applications worldwide are the largest users of geothermal energy, non-electrical uses in the United States are still relatively undeveloped. In 1975, less than five percent of the heat extracted from geothermal resources in the United States was used in direct thermal applications.[2] The U.S. Department of Energy anticipates that by 1985 direct thermal uses will represent one-fourth to one-third of the total usage of geothermal energy in the U.S.[3]

Some of the anticipated direct thermal uses of geothermal energy are shown in Figure 8-12. Direct thermal applications can utilize the heat of low-to-medium temperature geothermal resource more efficiently than electric power generation. Since geothermal resources of low-to-medium temperature are larger than those of high temperature, non-electrical applications also have the largest potential resource base.[4]

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[1] Howard, J. H. "Principal Conclusions of the Committee on the Challenges of Modern Society Non-Electrical Applications Project." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 2127-2139.

[2] *Ibid.*

[3] U.S. Energy Research and Development Administration. Program Approval Document, Geothermal Energy Development, Fiscal Year 1977. January 17, 1977. p. 3.

[4] Reistad, G. M. "Potential for Nonelectrical Applications of Geothermal Energy and Their Place in the National Economy." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 2155-2164.

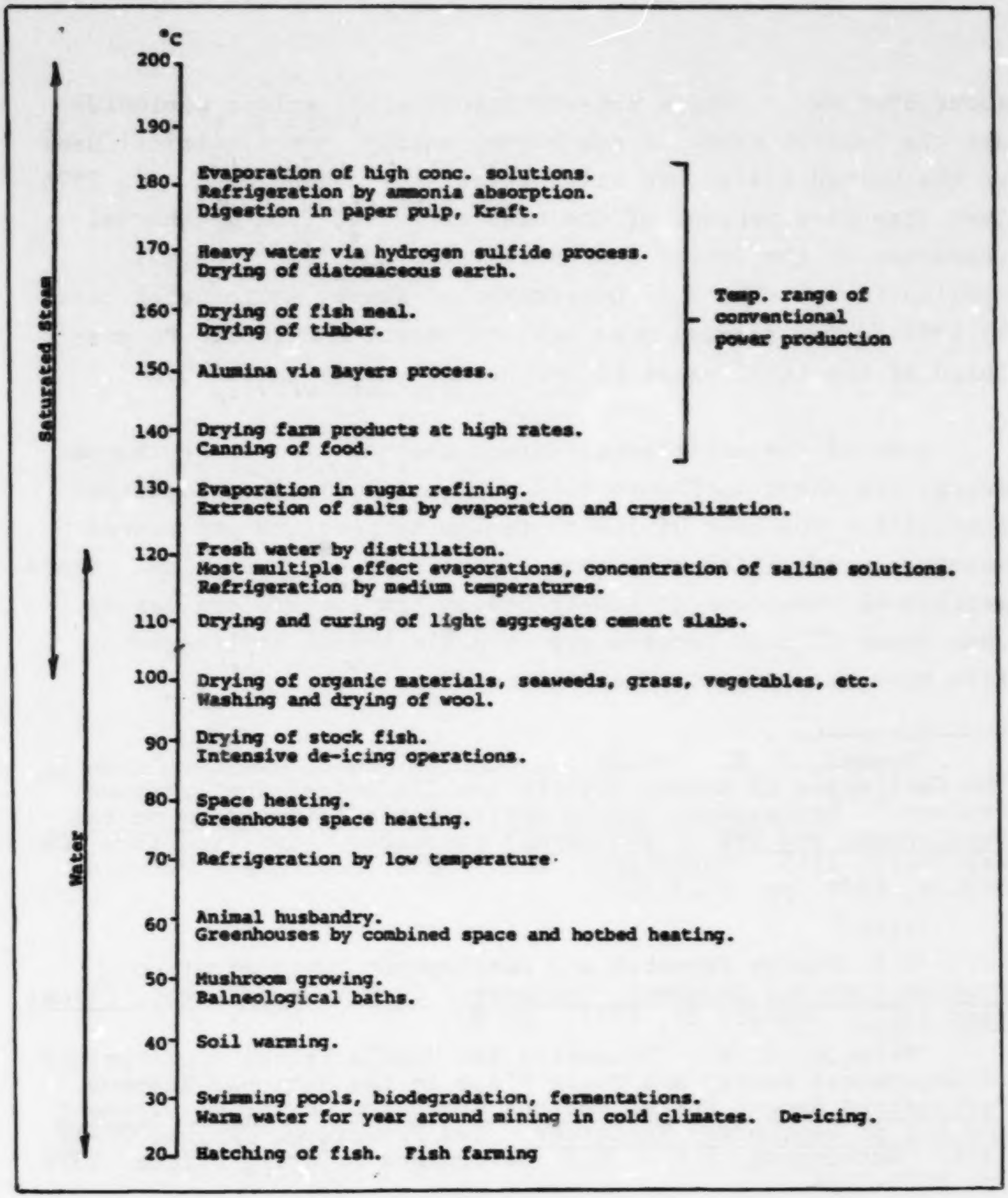
°C
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
Saturated Steam
Water
Evaporation of high conc. solutions.
Refrigeration by ammonia absorption.
Digestion in paper pulp, Kraft.
Heavy water via hydrogen sulfide process.
Drying of diatomaceous earth.
Drying of fish meal.
Drying of timber.
Alumina via Bayers process.
Drying farm products at high rates.
Canning of food.
Temp. range of conventional power production
Evaporation in sugar refining.
Extraction of salts by evaporation and crystalization.
Fresh water by distillation.
Most multiple effect evaporations, concentration of saline solutions.
Refrigeration by medium temperatures.
Drying and curing of light aggregate cement slabs.
Drying of organic materials, seaweeds, grass, vegetables, etc.
Washing and drying of wool.
Drying of stock fish.
Intensive de-icing operations.
Space heating.
Greenhouse space heating.
Refrigeration by low temperature.
Animal husbandry.
Greenhouses by combined space and hotbed heating.
Mushroom growing.
Balneological baths.
Soil warming.
Swimming pools, biodegradation, fermentations.
Warm water for year around mining in cold climates. De-icing.
Hatching of fish. Fish farming

Figure 8-12. Recommended Temperature of Geothermal Fluids for Various Direct Thermal and Other Non-Electrical Applications.

Source: Lindal, B. "Industrial and Other Applications of Geothermal Energy." Geothermal Energy. H. C. H. Armstead, (ed.). Paris: UNESCO, LC No. 72-07138, pp. 135-148.

Geothermal energy can be utilized in certain "multipurpose" developments. As one example, at the Raft River Geothermal Project in Idaho, a 300°F resource is being developed to furnish electricity, industrial process heat, and district heating.[1] Such multipurpose developments are mostly confined to geothermal resources containing few dissolved solids.

The following sections provide a brief overview of direct thermal and other non-electrical applications of geothermal energy. A discussion of residential and commercial applications, agricultural applications and related topics, and industrial applications follows. Since non-electrical uses of geothermal energy are diverse, no input/output data for non-electrical applications are provided. Such data are largely unavailable. Some economic data are presented in the final section.

The following discussion draws heavily from a paper by J. H. Howard.[2]

8.7.4.1 Residential and Commercial Applications

In 1975, the world-wide use of geothermal energy for commercial and residential applications represented an average energy consumption of about 400 MW_t. Uses in these applications are chiefly space and district heating and cooling.[3]

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[1] Idaho National Engineering Laboratory. Idaho Geothermal Development Projects, Report for the Year Ending February 1976. U.S. Energy Research and Development Administration, 1976.

[2] Howard, J. H. "Principal Conclusions of the Committee on the Challenges of Modern Society Non-Electrical Applications Project." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office. 1976. pp. 2127-2139.

[3] *Ibid.*

In the United States, geothermal waters have been used to heat homes and buildings in Boise, Idaho and Klamath Falls, Oregon. Other countries with large space and district heating applications are Iceland, Hungary, the Soviet Union, France, New Zealand, and Japan. The largest application is found in Reykjavik, Iceland, where the average energy consumption was about 170 MW_t in 1975.[1]

Hot-water and forced-air residential heating systems are easily adapted for the use of geothermal energy. If scaling and corrosion are minimal, the geothermal fluid can be used directly in existing hot-water equipment. In forced-air systems, the temperature of the hot air leaving the heater is usually around 55 to 60°C. Geothermal fluids with temperatures around 70 to 80°C or greater are sufficient for this application. The furnace and fan of the present forced air systems are replaced by a surface heat exchanger and a somewhat larger fan.[2]

The Rotarua International Hotel in New Zealand features a geothermal heating and cooling system consisting of a lithium bromide absorption unit designed for climate temperatures from -4°C to +30°C.[3] Geothermal heating and cooling systems using ammonia absorption are also feasible.[4]

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[1] Howard, J. H. "Principal Conclusions of the Committee on the Challenges of Modern Society Non-Electrical Applications Project." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 2127-2139.

[2] *Ibid.*.

[3] *Ibid.*

[4] Taylor, R. J., W. J. Toth, and D. W. Stowe. "Ammonia Absorption Geothermal District Heating and Air-Conditioning System." QM-77-018, Applied Physics Laboratory, John Hopkins University. March 1, 1977.

8.7.4.2 Agricultural Applications

In 1975, the average worldwide usage of geothermal energy in agricultural applications amounted to about 5500 MW_t, or over 90 percent of total usage of geothermal energy in non-electrical applications. Two uses have been identified: heating (in greenhouses, animal husbandry, and aquaculture), and irrigation. These applications are discussed briefly below.[1]

The largest agricultural application of geothermal waters is in greenhouses for both heating and irrigation. Over 90 percent of the geothermal energy used in agricultural applications is associated with large acreages of greenhouses in the Soviet Union. This application is more common in areas where the growing season is short. Most geothermally heated greenhouses use geothermal waters directly on the soil alone or mixed with cool potable or irrigation waters.[2,3]

Advantages of using geothermal waters in greenhouses include increased crop yields, year-round crop cultivation, and control of predators, pests, and frosts.[4] In the United States, soil warming in field experiments near Corvallis, Oregon increased the yield of corn silage by 45 percent, tomatoes by 50 percent, soybean silage by 66 percent, and beans by 39 percent. Relatively pure geothermal waters are required if the waters are directly applied to the soil. More saline waters would require the transfer of heat via surface heat exchangers.[1]

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[1] Howard, J. H. "Principal Conclusions of the Committee on the Challenges of Modern Society Non-Electrical Applications Project." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 2127-2139.

[2] *Ibid.*

[3] Howard, J. H., ed. Present Status and Future Prospects for Nonelectrical Uses of Geothermal Energy. UCRL-51926. Lawrence Livermore Laboratory. Livermore, CA: University of California, October 3, 1975.

[4] Cheremisinoff, P. N. and A. C. Morresi. Geothermal Energy Technology Assessment. Westport, Conn.: Technomic Publishing Company, 1976, p. 107.

Relatively pure geothermal waters may be directly applied to lands for irrigation of crops. This is especially attractive in arid areas.[2]

In animal husbandry, geothermal waters are used not only for space heating, but also for the cleaning, sanitizing, and drying of animal shelters and wastes. Poultry, swine, and cattle respond to optimum thermal environments with increased production, growth rate, and feeding efficiency.[3,4]

Aquaculture is "the practice of cultivating aquatic species under controlled environmental conditions in order to establish and maintain optimal environmental conditions year-round for increased rate of growth and feed efficiency."[5] Geothermal waters can supply the heat required to maintain optimum temperatures.

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[1] Howard, J. H., ed. Present Status and Future Prospects for Nonelectrical Uses of Geothermal Energy. UCRL-51926. Lawrence Livermore Laboratory. Livermore, CA: University of California, October 3, 1975, pp. 62-64.

[2] *Ibid.*, pp. 108-109.

[3] *Ibid.*, p. 64.

[4] Yarosh, M. M., et al. Agricultural and Aquacultural Uses of Waste Heat. Report Number ORNL-4797. Oak Ridge National Laboratory, 1972.

[5] Howard, J. H., ed., *op.cit.*, pp. 62-64.

8.7.4.3 Industrial Applications

Present industrial applications of geothermal energy have been summarized by Howard[1] and are shown in Table 8-60. The average energy consumption of these applications represents a total utilization of 150-200 MW_t of geothermal energy.

Geothermal fluids can supply industry with direct heat, process steam, and raw materials. Applications using the geothermal resource as a source of heat or steam include: process heating, evaporation, drying, distillation, refrigeration by absorption machines, sterilization, washing, and de-icing (as in mining operations). Raw materials contained in geothermal waters include salts and other valuable chemicals.[2] Methods for the extraction of potassium, lithium, and calcium are available. The Italians formerly extracted large quantities of boric acid, ammonium bicarbonate, ammonium sulfate, and sulfur from the steam jets at Larderello. Processes are being developed in the Soviet Union for the extraction of alkali and alkali-earth metals, and trace elements.[3] In particular, the geopressured region of the Gulf Coast contains significant quantities of methane. In some instances, geopressured resources may be important simply for the recovery of methane.

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[1] Howard, J. H. "Principal Conclusions of the Committee on the Challenges of Modern Society Non-Electrical Applications Project." Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office, 1976, pp. 2127-2139.

[2] Howard, J. H., ed. Present Status and Future Prospects for Nonelectrical Uses of Geothermal Energy. UCRL-51926. Lawrence Livermore Laboratory. Livermore, CA: University of California, October 3, 1975.

[3] Stevovich, V. A. Geothermal Energy. Contract No. MDA-903-76C-0099. Defense Advanced Research Projects Agency. Washington, D.C.: November 1975, pp. 196-203.

TABLE 8-60. PRESENT INDUSTRIAL APPLICATIONS OF GEOTHERMAL ENERGY

Application	Country	Description of Application	Production Steam Flow Rate, or Water Flow Rate	Associated Power In Megawatts[a]	Comments
Wood and paper industry					
Pulp and paper	New Zealand	Processing and a small amount of electrical power generation. Kraft process used.	~400,000 lbs/hr of steam.	100 to 125	Geothermal energy delivered to mills by 80,000 lb/hr of 200 psig steam and 32,000 lb/hr of 100 psig steam which are obtained by flashing wet steam at the wellbore.
Veneer factory	New Zealand				No details given.
Timber drying	New Zealand	Kiln operation			No details given.
Washing and drying of wood	Iceland	Steam drying			No details furnished. Reported to occur in other places.
Mining					
Diatomaceous Earth plant	Iceland	Production of dryed diatomaceous earth recovered by wet mining techniques	Up to 30 tons/hr ~35 of steam at 183°C/10 atg. Total steam consumption 40 to 30 tons/hr according to the season. Wellbore flow—184.8 Gcal/hr. Utilized—30.5 Gcal/hr.		Dredging in the lake is done only in the summer while the plant runs throughout the year. The reported 30.5 Gcal/hr appears to be high or assumes superheated steam at 10 atg.
Chemicals					
Salt plant	Japan	Production of salt from sea water.	~150 tons salt/year		No longer in operation
Salt plant	Philippines	Production of salt from sea water		<2.5	Sea water brought 3 km to plant. Three grades of salt produced.
Sulfur mining	Japan	Sulfur extraction from the gases issuing from a volcano			Unsophisticated operation that has become uneconomic.
Calcium chloride	United States[b]	Recovery of potassium chloride from the geothermal brine	Uncertain but small.		
Boric acid	Italy	Geothermal steam is used for processing imported ones.	30 tons steam/hr	~15 to 19	
Boric acid, ammonium bicarbonate, ammonium sulfate, sulfur		Recovery of substances from the volatile components which accompany the geothermal steam.	No longer in operation. Large production before 1966.		
Dry ice	United States[b]	Production of dry ice from CO_2 in the Salton Sea geothermal area.			
Miscellaneous					
Confectionary industry	Japan		Daily rice processing capacity 180 kg.		Few details given, uses 98°C water, spring source.
Grain drying	Philippines	Geothermal steam heats rotary kiln dryer.		<2.5	Palay drying time cut to 10 minutes from 4-8 hrs. Model under test.
Brewing and distillation	Japan		Uncertain but small		No details given. One well used.
Stock fish drying	Iceland	Fish drying in shelf dryers.			Uses excess water from commercial heating system in Reykjavik during summer in local stock fish processing center.
Curing cement building slabs	Iceland	Curing of light aggregate cement building slabs			No details given.
Washing and drying of wool					No details given. Reported to occur in two or more countries.
Seaweed	Iceland	Drying seaweed for export.	~80 l/sec at 100°C Production of 3600 tons of dry seaweed per year. Each ton requires $3.40 worth of energy per ton of seaweed if the energy costs $0.45 per Gcal.	~3 to 4	Description of proposed system given, only word-of-mouth indication that system is presently in operation.

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[a] The "associated power in megawatts" entry is an estimate of the rate at which energy is supplied to and available to be utilized by the process, usually not the energy flow rate from the well.

[b] Current status of application is unknown.

Source: Howard J. H. "Principal Conclusions of the Committee on the Challenges of Modern Society Non-Electrical Applications Project." *Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources*. San Francisco, CA, May 20-29, 1975. Washington, D.C.: U.S. Government Printing Office. 1976. pp. 2127-2139.

8.7.4.4 Economics

D. F. Towse[1] has estimated the costs of various non-electrical utilizations of geothermal energy. These preliminary costs estimates are presented as Table 8-61. The costs are based largely on experience for Klamath Falls, Oregon,[2] Iceland,[3] and the Imperial Valley of California,[4] and a feasibility study of the Gulf Coast.[5]

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[1] Howard, J. H., ed. Present Status and Future Prospects for Nonelectrical Uses of Geothermal Energy. UCRL-51926. Lawrence Livermore Laboratory. Livermore, CA: University of California, October 3, 1975, pp. 80-86.

[2] Culver, G., J. W. Lund, and L. Svanevik. Klamath Falls Hot Water Well Study. UCRL-13614. Lawrence Livermore Laboratory, 1974.

[3] Zoega, J. "The Reykjavik Municipal Heating System." Proceedings International Conference on Geothermal Energy for Industrial, Agricultural, and Commercial-Residential Uses. Klamath Falls, Oregon: Oregon Institute of Technology, 1974.

[4] U.S. Department of the Interior, Bureau of Reclamation. Geothermal Resource Investigations, East Mesa Test Site, Imperial Valley, CA. Status Report, November 1974.

[5] DES Engineers, Inc. Geothermal Resource Utilization - Paper and Cane Sugar Industries. UCRL-13633. Lawrence Livermore Laboratory, 1975.

TABLE 8-61. ESTIMATED COSTS OF NON-ELECTRICAL UTILIZATIONS OF GEOTHERMAL ENERGY

Example number	Heat utilization* (10^6 Btu/hr.)	Type of example	Number of users	10^6 Btu/hr. per user	Capital costs ($)		Annual geothermal fuel costs per user	Costs per 10^6 Btu used ($)	Notes
					Wells	Distribution			
1	2,500,000	Pulp & Paper Mill	1	2,500,000	15,700,000	0	2,905,000	1.162	(1)
2	419,000	Industrial freezing	1	419,000	2,720,000	0	496,096	1.184	(1)
3	200,000	Industrial refrigeration	1	200,000	870,000	0	154,000	0.770	(2)
4	84,100	Food processing	1	84,100	470,000	0	85,362	1.015	(3)
5	84,100	Commercial bldgs-heat	10	8,410	470,000	25,000	8,965	1.066	(3)
6	55,100	Industrial drying	1	55,100	470,000	0	85,349	1.549	(4)
7	55,100	Commercial bldgs. (heat & cool)	10	5,510	470,000	25,000	8,970	1.628	(4)
8	25,000	College	1	25,000	40,000	0	16,925	0.667	(5)
9	25,000	(4 Hospitals)	4	6,250	40,000	10,000	4,538	0.726	
10	25,000	(10 Commercial Buildings)	10	2,500	40,000	25,000	2,000	0.800	(5)
11	25,000	(100 Single-family residences)	100	250	40,000	250,000	476	1.906	(5)
12	2,453	Commercial-heating	1	2,453	7,000	0	912	0.372	(6)
13	2,453	Single-family residences	10	245	7,000	25,000	549	2.242	(6)
14	175	Single-family residences	1	175	7,000	0	912	5.217	(6)

NOTES

(1) 13,000' deep 250°F U.S. Gulf Coast
(2) 8,500' deep 180°F U.S. Gulf Coast
(3) 6,000' deep 225°F Imperial Valley
(4) 6,000' deep 225°F Imperial Valley
(5) Large System, Klamath Falls, Oregon - ~190°F
(6) Small System, Klamath Falls, Oregon - ~190°F

* Not to be confused with capacity of the system to produce heat energy; i.e., this expresses heat actually used, rather than potential for providing heat.

Source: Howard, J. H., ed. Present Status and Future Prospects for Nonelectrical Uses of Geothermal Energy. UCRL-51926. Lawrence Livermore Laboratory. Livermore, CA: University of California, October 3, 1975, p. 82.

★ U.S. GOVERNMENT PRINTING OFFICE: 1979 -281-147/36